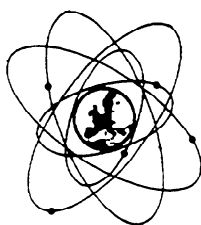


J. G. WALFORD AND A. F. THOMAS, "THE EQUIPMENT AND METHODS USED IN BRITISH CRITICALITY LABORATORIES," IN CRITICALITY CONTROL IN CHEMICAL AND METALLURGICAL PLANT, KARLSRUHE SYMPOSIUM, 1961 (ORGANISATION FOR ECONOMIC COOPERATION AND DEVELOPMENT, EUROPEAN NUCLEAR ENERGY AGENCY, PARIS, 1961) PP. 553-588.

CRITICALITY CONTROL
IN CHEMICAL AND METALLURGICAL PLANT

CONTROLE DE LA CRITICALITE
DANS LES INSTALLATIONS CHIMIQUES ET MÉTALLURGIQUES



KARLSRUHE SYMPOSIUM
1981

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT
EUROPEAN NUCLEAR ENERGY AGENCY

ORGANISATION DE COOPÉRATION ET DE DÉVELOPPEMENT ÉCONOMIQUES
AGENCE EUROPÉENNE POUR L'ÉNERGIE NUCLÉAIRE

L'Organisation de Coopération et de Développement Économiques a été instituée par une Convention signée le 14 décembre 1960, à Paris, par les Membres de l'Organisation Européenne de Coopération Économique, ainsi que par le Canada et les États-Unis. Aux termes de cette Convention, l'O.C.D.E. a pour objectif de promouvoir des politiques visant :

- à réaliser la plus forte expansion possible de l'économie et de l'emploi et une progression du niveau de vie dans les pays Membres, tout en maintenant la stabilité financière, et à contribuer ainsi au développement de l'économie mondiale ;
- à contribuer à une saine expansion économique dans les pays Membres, ainsi que non membres, en voie de développement économique ;
- à contribuer à l'expansion du commerce mondial sur une base multilatérale et non discriminatoire, conformément aux obligations internationales.

La personnalité juridique que possédait l'Organisation Européenne de Coopération Économique se continue dans l'O.C.D.E., dont la création a pris effet le 30 septembre 1961.

Les Membres de l'O.C.D.E. sont : la République fédérale d'Allemagne, l'Autriche, la Belgique, le Canada, le Danemark, l'Espagne, les États-Unis, la France, la Grèce, l'Irlande, l'Islande, l'Italie, le Luxembourg, la Norvège, les Pays-Bas, le Portugal, le Royaume-Uni, la Suède, la Suisse, la Turquie,

L'Agence Européenne pour l'Énergie Nucléaire (ENEA) a été créée en décembre 1957 dans le cadre de l'O.E.C.E. afin de développer la collaboration atomique entre l'ensemble des pays de l'Europe occidentale. Un Comité de Direction de l'Énergie Nucléaire comprenant des représentants de tous les pays Membres et Associés est l'organe directeur de l'ENEA.

L'Agence a pour fonctions de (a) créer des entreprises communes ; trois entreprises ont été constituées : la Société Eurochemic pour le retraitement des combustibles irradiés (à Mol, Belgique), le Projet de réacteur à eau lourde bouillante de Halden (Norvège), le Projet Dragon de réacteur à haute température refroidi par gaz (à Winfrith, Royaume-Uni) ; (b) harmoniser les programmes de recherches en facilitant la coopération entre les pays Membres dans les domaines scientifiques et techniques, les échanges de personnel et d'informations ; (c) élaborer des règles uniformes en matière nucléaire pour l'ensemble de l'Europe, notamment dans les domaines de la santé et de la sécurité, du transport des matières radioactives, de la responsabilité civile et des assurances ; (d) étudier les aspects économiques de l'énergie nucléaire en examinant périodiquement les programmes nationaux, la place de l'énergie nucléaire dans la balance énergétique de l'Europe et le marché des combustibles, matériaux et équipements nucléaires.

L'ENEA travaille en liaison avec les autres organisations internationales intéressées, particulièrement avec l'Euratom et l'Agence Internationale de l'Énergie Atomique.

The Organisation for Economic Co-operation and Development was set up under a Convention signed in Paris on 14th December 1960 by the Member countries of the Organisation for European Economic Co-operation and by Canada and the United States. This Convention provides that the O.E.C.D. shall promote policies designed:

- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
- to contribute to sound economic expansion in Member as well as non-Member countries in the process of economic development;
- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The legal personality possessed by the Organisation for European Economic Co-operation continues in the O.E.C.D., which came into being on 30th September 1961.

The Members of O.E.C.D. are: Austria, Belgium, Canada, Denmark, France, the Federal Republic of Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States.

The European Nuclear Energy Agency (ENEA) was set up in December 1957 as part of the O.E.E.C. to develop nuclear collaboration between the countries of Western Europe. A Steering Committee for Nuclear Energy, composed of representatives from all Member and Associated countries, is the controlling body of ENEA.

The work of the Agency comprises (a) creation of joint undertakings, three of which — the Eurochemic Company for reprocessing irradiated fuels at Mol in Belgium, the Halden boiling heavy water reactor project in Norway, and the Dragon high-temperature gas-cooled reactor project at Winfrith in the United Kingdom — are already in operation; (b) the harmonisation of research programmes, encouraging scientific and technical co-operation between Member countries and the exchange of information and personnel; (c) the establishment of uniform atomic regulations for Europe, especially in the fields of health and safety, liability and insurance in case of accident, and the transport of radioactive materials; (d) the study of the economic aspects of nuclear energy, by a regular examination of national programmes, of the place of nuclear energy in Europe's overall energy balance sheet, and of the markets for nuclear fuels, materials and equipment.

ENEA works in liaison with the other international organisations concerned, especially Euratom and the International Atomic Energy Agency.

THE EQUIPMENT AND METHODS USED IN BRITISH CRITICALITY LABORATORIES

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INTRODUCTION

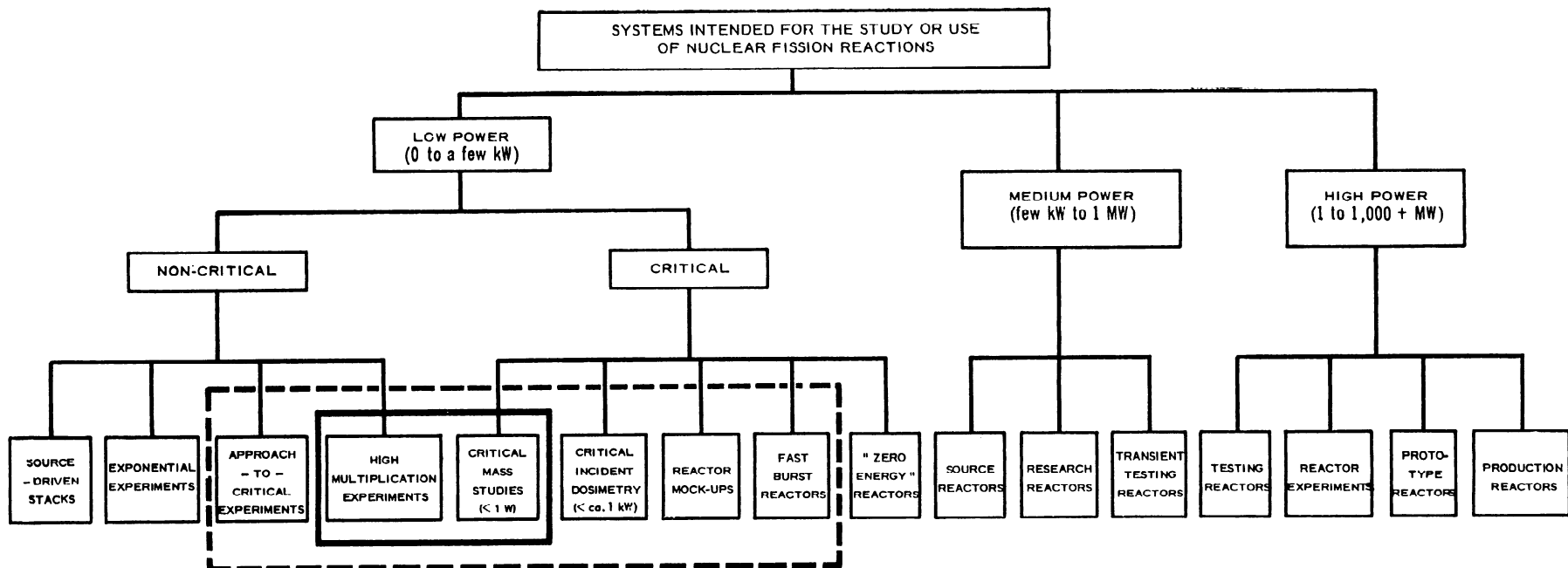
Experimental criticality studies occupy a somewhat specialized position, shown diagrammatically in Figure 1, within the much broader field of reactor physics research. They have, as their ultimate purpose, the prevention of criticality in processing plants, laboratories, fissile material stores and other places where it must at all costs be avoided, in contrast to other reactor physics studies which are aimed at the efficient attainment of a nuclear reaction where criticality is an essential.

This difference in purpose is reflected in the design of facilities and equipment, in the experimental techniques and in the organisation of the two types of reactor studies; at the same time, each field can contribute very usefully to the needs of the other. On the one hand, every measurement made in exponential experiments and zero-energy reactors can be said to be of some potential value in the safety assessment of processing plant. On the other hand, well-designed critical assembly experiments can and should be used to yield data of fundamental value in reactor analysis; indeed, it is extremely desirable from an economic standpoint that they should be so used.

Critical facilities can also contribute directly in a wider sphere since they can be used for setting up simplified reactor mock-ups in the earliest stages of a reactor project, for the operation of pulsed or 'fast burst' reactors, and for certain types of irradiation and dosimetry experiments. At the other end of the power scale, the facilities are used for subcritical neutronic experiments such as interaction parameter studies and accurate multiplication measurements, which are often adequate in themselves for nuclear safety assessments. These several extensions of the scope of critical assembly laboratories are shown within the broken line in Figure 1.

CRITICAL ASSEMBLY LABORATORIES

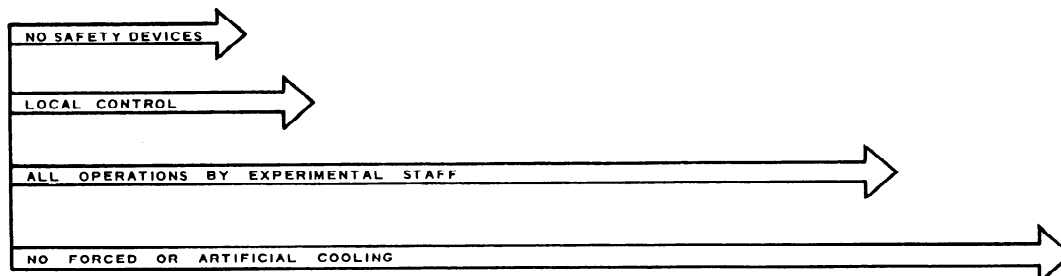
Critical experiments on behalf of plant safety have been in progress in the United Kingdom for almost ten years and have been carried out at three different A.E.A. Establishments — Harwell, Aldermaston and Dounreay — of which only the last two are in use at present. The division of work between these laboratories has depended primarily on the physical form of the fissile materials, experiments with metals being carried out almost entirely at Aldermaston and those with solutions at Harwell (up to 1957) and Doun-



EXAMPLES:

HELEN	*	ATLAS	PUMA	TESSIE	HFIR & GODIVA	ZEPHYR	NESTOR	LIDO	SPERT	DIDO	DFR	CALDER	WINDSCALE
SCORPIO	(See note below)	ERIC	PANTHER	ORNL Tank	APPR KUKLA	DIMPLE	WBNS	GLEEP	BORAX	ETR	DRAGON	PFR	CALDER HALL
BICEP		WATERFALL	TESSIE	Experiments	(ORNL)	HERO	AFSR		KEWB	DMTR	HRT		NPR
		HAZEL	PHOENIX			HORACE			TREAT		PRTR		

LIMITING FACTORS:



MAIN FIELD OF CRITICALITY STUDIES



ADDITIONAL SCOPE OF CRITICALITY LABORATORIES

* Note: Includes "interaction parameter" studies and multiplication experiments giving critical parameters by long extrapolation.

Figure 1. The position of critical assembly laboratories within the field of reactor studies.

TABLE I. COMPARATIVE FEATURES OF UNITED KINGDOM CRITICAL ASSEMBLY LABORATORIES AND CELLS

Location	A.E.R.E. (Harwell) (Typical Cell)	A.W.R.E. (Aldermaston)	D.E.R.E. (Dounreay)			
			Cell 1	Cell 2	Cell 3	Cell 4
Date of operation	1952-1957	From 1952	From 1957	1959-61	from Nov. 1959	from Nov. 1960
Main types of experiments	Light and heavy water solutions of Pu, U 235 and U 233 in simple geometry	Metals and moderated solids (U 235 and Pu); interaction studies	Solutions of U 235; including large systems and <i>ad hoc</i> tests on process vessels	Solutions of U 235 in simple geometry (up to 3 ft over-all dia.)	Moderated solids (U 235), especially large and heavy systems; interaction studies on solutions and solids	Plutonium solutions and moderated solids, usually in simple geometry
Number of rigs accommodated	One	Three	One or two	One	One	Two
Control room position	Local	Remote (100 yds)	Remote (100 yds)	Local	Local	Local
Exclusion area	On rear side of cell; also on upper floors of building	100 yds radius	100 yd radius; also earth embankment on open side of cell	None	None	None
Shielding material and thickness	Temporary concrete cairn (3 walls: 3 ft roof and usually none on rear wall)	Brick (1 ft) (normal structure, with unshielded doors and windows)	Concrete (1.5 ft) on three walls; <i>none</i> on fourth wall and roof	Below ground (rock) (concrete roof: 2 ft minimum)	Concrete (walls, 5 ft., roof, 2 ft)	Concrete (walls, 5 ft., roof, 2 ft)
Containment	None	None	None	None	Not designed, but all cell entrances and ducts can be closed	Steel pressure vessel (leakage < 0.3 %/24 hr at 10 lb/in. ² pressure)
Dimensions (ft): length breadth height	12 12 30	30 30 22 (also 8 ft deep well in floor)	25 15 18.5 (also 7 ft high, 7 ft square extension above roof)	10 10 10	27 17 18	27 dia. — 22.5 (also 10 ft deep, 12 ft square pit in floor)
Ventilation	None, apart from glove-box extract and general active area ventilation	Unfiltered extract; filtered and heated input	None (can be open to atmosphere)	Recirculation and low capacity extract through filter	Filtered extract: filtered and heated input (both ducts sealed on emergency trip)	i) Cell <i>open</i> - filtered extract to stack; heated and filtered input. ii) Cell <i>closed</i> - recirculation through filter and heater
Temperature control	Conventional	Conventional	None	Conventional	± 2° C (no cooling)	± 2° C (no cooling)
Access to cell: personnel equipment	Removable labyrinth of concrete blocks Rear side of glove-box (open)	Normal doors Double doors	Steel door Double doors in thin front wall	Labyrinth and stairs (removable blocks) By removal of concrete roof beams	Labyrinth (fixed) By removal of concrete blocks in 12 × 8 ft hole in end wall	Removable labyrinth in concrete and wicket door in pressure vessel Steel plant door, 8 ft square, in pressure vessel wall
Ancillary services: solution storage	e.g. 600 litres (2 tanks)	None	600 litres (8 tanks)	150 litres (2 tanks)	Up to 100 litres (temporary only)	550 litres (7 tanks)
solution processing	Available on site	None	Two batch evaporators (4 litres/hr total)	—	None	Continuous evaporator (5 litres/hr)
Metal processing Moderated solid processing	— —	Available on site Available on site	— Recovery line for U/H mixtures	— U/H mixtures	Storage only	— Fabrication line for Pu/H tablets
Lifting capacity in cell	e.g. 5-ton gantry for cell erection	2.5-ton gantry; mobile hand hoist	2-ton monorail; 2 × 0.25 ton monorails	None	3-ton gantry	2-ton monorail (internal) 2-ton monorail (external)

reay. Work on solids other than metals including, in particular, mixtures of fissile material and moderator, is currently in progress at both Aldermaston and Dounreay.

The design of the facilities and the experimental procedures at the three sites have been somewhat different and they are described separately. The main features of the several facilities are summarized in Table I.

Harwell

No laboratory intended specifically for criticality studies was set up at Harwell. The experiments all employed aqueous solutions of the three fissile isotopes (Table II) and were carried out at intervals between 1952 and 1957 in a succession of temporary concrete cairns erected inside buildings used for chemical engineering research ^(1,3). Each cell was relatively small in size (approx. 12 ft square) and contained only the critical assembly itself, the storage and dispensing equipment for the fuel solutions and all control and nuclear instrumentation being located in separate cubicles just outside the 3 ft thick cell walls. The cells were not contained in any way, though all were situated in active areas having filtered extract ventilation. It was a feature of the operational procedure at Harwell that no assembly was taken nearer to critical than 98 % or 99 % of the critical mass.

TABLE II. CRITICAL EXPERIMENTS CARRIED OUT AT HARWELL
(Systems of interest in the nuclear safety field)

Fissile isotope (X)	I	II	III	IV
	Pu 239	U 233	U 234 (45 %)	U 235 (45 %)
Moderator.....	Water	Water	Water	D ₂ O
Chemical form	Nitrate solution (acidity 1.7 N)	UO ₂ F ₂	UO ₂ F ₂	UO ₂ F ₂
Core shape	Cylinder	Cylinder	Cylinder	Cylinder
Core diameter (cm)	30.5	30.5	30.5	71
Reflector: radial	Water	Water	Water	Graphite (46 cm)
axial	None	None	None	None
H/X ratio: min.	400	250	260	1940
max.	890	850	680	6720
Apparatus	ZETR. 0	ZETR. 1a	Zetr. 1a	HAZEL
Date	1952	1956	1955	1957

Aldermaston

At Aldermaston, various critical assembly tests and critical mass determinations have been made in a facility comprising a single large experimental cell operated from a control room 100 yards away ⁽⁴⁾. The cell is of conventional brick construction and is surrounded by an exclusion area of 100 yards radius, from which all persons must be evacuated when a critical experiment is in progress.

The experimental cell is 30 ft square and 22 ft high and is thus large enough to house three critical assembly machines (ERIC, WATERFALL and ATLAS, Tables III and IV). It is a disadvantage that only one of these can be used at one time, and also that setting-up work cannot be carried out on one machine while another is being used in an approach-to-critical experi-

ment. It is possible, however, to change over the control equipment and radiation detectors from one machine to another in a few minutes.

The cell is equipped with an air-conditioning system providing a heated and filtered air input. There is no extract filter. It is the practice at Aldermaston, as it was at Harwell, to stop each approach experiment slightly short of the critical condition. The final subcritical reactivity depends on the nature of the experiment and may be as little as a few cents with a well understood metal assembly of 'clean' geometry, but is more usually 2 % or 3 % of the critical mass.

The equipment of the laboratory is of a kind appropriate to solid criticality work. The cell itself contains a 2.5-ton gantry crane with electric hoist, a mobile hand crane, and a fume hood for building up small fuel sub-assemblies and for cleaning and monitoring fissile components. Adjacent to the cell are a change room, a small workshop and a plant room; a store for machine accessories, solid reflector materials and portable neutron sources lies a short distance from the cell. There are no facilities for solution handling nor for the storage of fissile solutions.

Dounreay

Construction of the Dounreay facility started in 1956 and the first of four experimental cells became operational in 1957⁽⁵⁾. Two further cells, completing the part of the laboratory intended for uranium work, came into use during 1959. A fourth cell, designed primarily for experiments with plutonium-bearing materials, has recently been brought into use. A site plan of the area is shown in Figure 2 and a photograph of the facility in Figure 3.

The first cell resembles that at Aldermaston in being operated from a control room 100 yards away. There is, however, provision for some additional attenuation of neutrons by 18-in. thick concrete walls on three sides of the cell and by an earth bank on the fourth. The cell has no installed ventilation system and is uncontained. It is considerably smaller than that at Aldermaston but can accommodate two critical assembly rigs without undue difficulty. It was intended for studies on the criticality of uranium solutions and has been used for this work almost exclusively. A semi-permanent solution handling system is installed, with storage capacity for 600 litres of fuel solution in eight separate vessels; part of the latter is located in an annex which also serves as a change room. This cell shares with that at Aldermaston the disadvantage that only one assembly rig can be operated at one time, with the further restriction that fuel solution for a later experiment cannot be prepared while an earlier one is in progress.

Cell 2 consists of an underground pit in the form of a 10-ft cube, covered by a roof of removable concrete shielding blocks. The control room is at ground level and to the side of the cell roof, entrance to the pit being by way of a labyrinth in the concrete cairn and a ladder. The working volume is sufficient for only a single rig of limited size; the cell has therefore been used entirely for studies on uranium solution systems up to 16 in. in core diameter. The cell is uncontained, but is provided with filtered extract and recirculatory ventilation of low capacity. All solution handling and storage equipment is outside the pit and can be used whatever the state of the critical experiment. This feature, together with the proximity of the control room, have made for considerably greater speed of working than is possible in Cell 1. The proximity of the cell walls to the core of an assembly render this cell

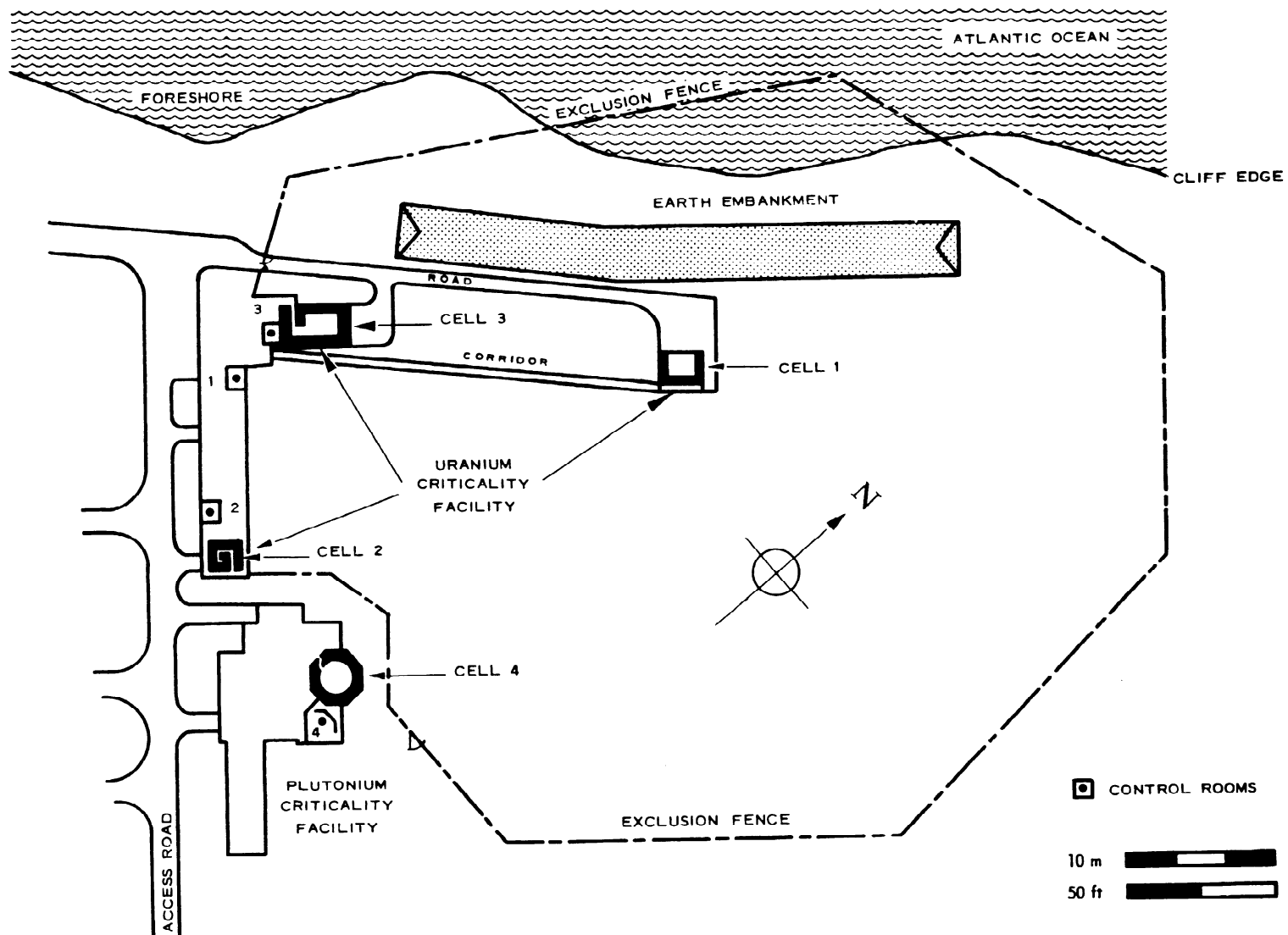


Figure 2. Site plan of the Dounreay criticality laboratory.

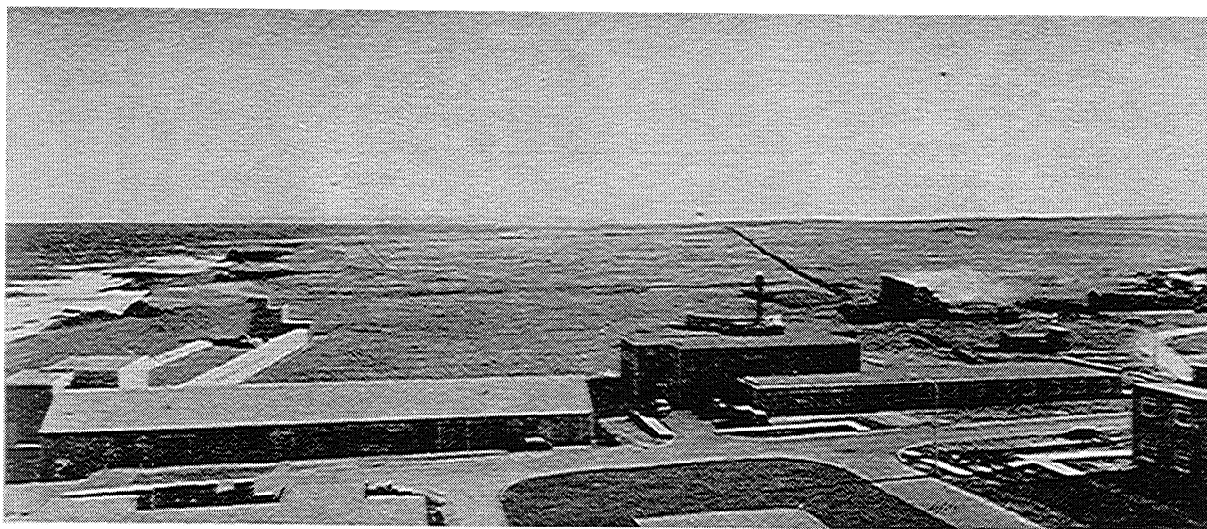


Figure 3. *The Dounreay criticality laboratory seen from the south-west.*

unsuitable for valid critical mass measurements on unreflected systems. Its small dimensions and the difficulty of access for large equipment have been a considerable inconvenience and have detracted from the safety of the work. For these reasons this cell, which was a temporary addition to the Dounreay resources, has recently been dismantled.

The third Dounreay cell is in the form of a concrete blockhouse, 27×17 ft in area and 18 ft high, with walls 5 ft thick and a roof 2 ft thick. The control room is situated alongside the cell, and access to the latter is by way of a labyrinth built into one of the concrete walls. In conformity with accepted United Kingdom philosophy, the cell shielding is designed to protect persons in the control room against the radiation from a critical incident yielding at least 10^{18} fissions and no exclusion area is required. The cell has its own separate input and extract ventilation systems, the former being heated; both are filtered and can be closed automatically by a trip signal. Although the cell cannot be sealed, its structure provides quite a high degree of containment of released activity.

Cell 3 was designed to house a single large assembly machine (TESSIE) for experiments on solid uranium systems up to twenty tons in weight. The equipment includes a three-ton gantry crane and a store for solid fuel units. Future experiments will employ uranium solutions contained in two or more interacting vessels (SIRIUS, see Table IV) and to provision these, two independent solution-handling systems with simple storage and glove box facilities have been installed.

The fourth Dounreay cell, intended specifically for work on plutonium systems, is considerably more elaborate than its predecessors and is housed in a separate building (Figure 4). It consists of a cylindrical steel shell of 27 ft dia. and 22.5 ft high, surrounded by a 5 ft thick concrete shield with a 2 ft thick roof. There is a steel-lined pit, 10 ft deep and 12 ft square, in the cell floor for housing dump tanks, control mechanisms, etc. An 8 ft square door in the steel shell, in line with a removable portion of the concrete shield, allows heavy plant to be brought into the cell; a smaller steel door and a labyrinth in the concrete are available for personnel access.

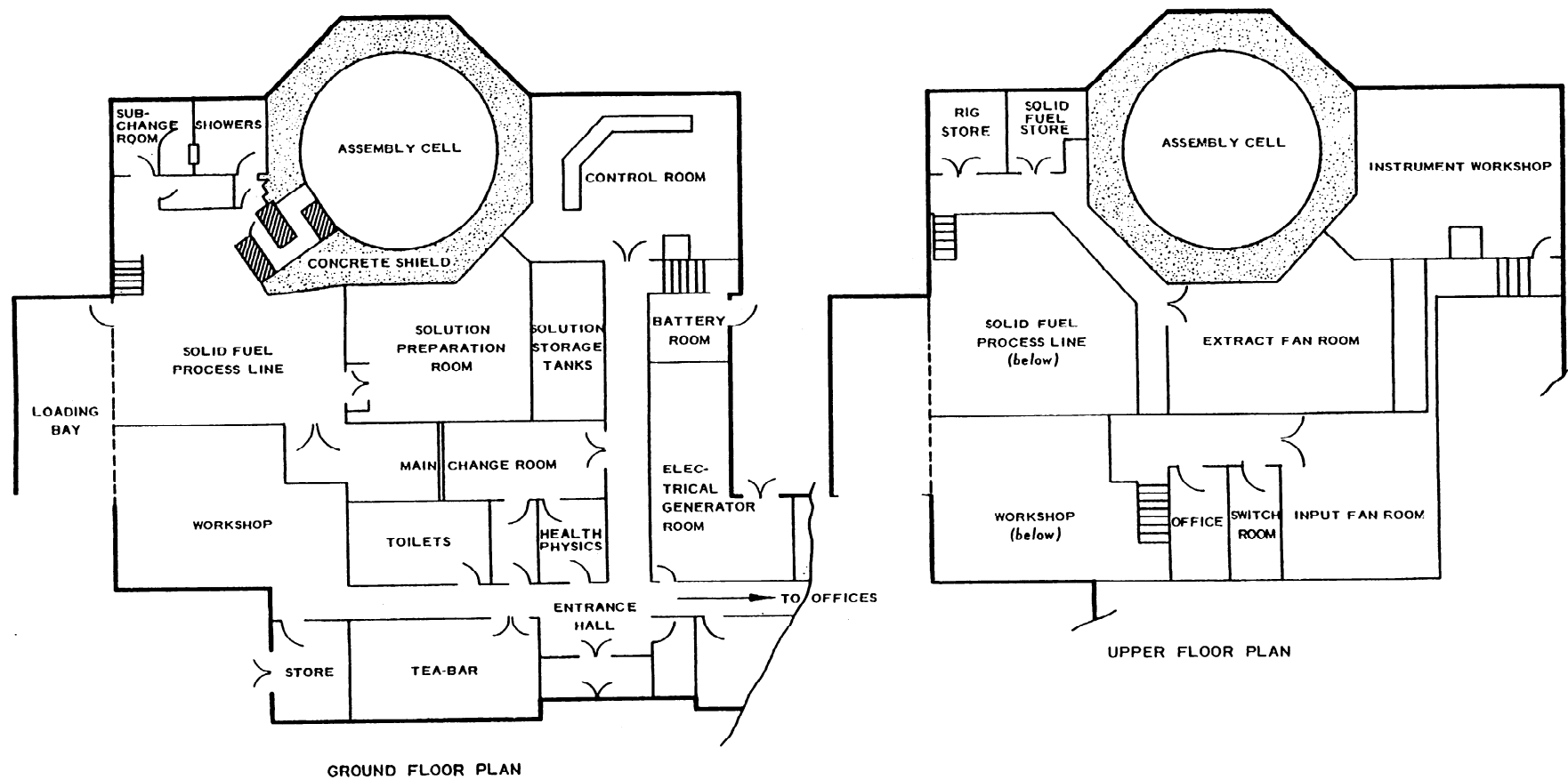


Figure 4. The Downreay plutonium criticality facility (Cell 4).

The steel shell provides a high degree of containment of radioactivity (shown on test to be much better than the specified maximum permitted leakage of 0.3 % per 24 hours at 10 lb/in.² excess pressure). To preserve this containment, all cables and pipes enter the cell through sealed service plugs; the larger and smaller doors are sealed and must be closed whenever reactivity is added to an assembly. No air lock is provided, the proposed procedure in the event of a critical incident being to keep the cell sealed until clean-up action can be taken by frog-suited workers. A sub-change room and control point, equipped with radio and television links to the cell, are provided for this purpose close to the cell entrance.

The cell is able to accommodate two critical assembly rigs, each housed within separate containment boxes having their own recirculatory ventilation systems. These are intended to minimise the spread of activity and to assist clean-up in the event of a critical incident. It is thought probable that the boxes prevent the general contamination of the cell unless the incident were unusually severe. The cell itself is equipped with a recirculatory ventilation system, comprising a filter and air heater, which serves both for temperature control (to within 2° C) and for clean-up. The main extract from the cell discharges through a filter to a stack and is operative only when the cell doors are open, the extract duct being sealed by a motor-driven valve during critical experiments.

Support facilities for the critical experiments are disposed as far as possible around the outside of the cell at two floor levels, with offices and general building services at a greater distance (Figure 4). The active facilities are on the side of the cell nearest its entrance and include two fuel processing laboratories, stores for solid and liquid fuels, the emergency change room already described and the extract fan room. These are separated by a fire-break wall from the inactive rooms, comprising the control room, an electronics laboratory which can be used to house the additional instruments needed in certain experiments, and a motor-generator plant giving stand-by electrical supplies from batteries. A main change room, health physics room, input fan room, small engineering workshop and staff accommodation complete the facility.

The uranium and plutonium criticality laboratories at Dounreay include limited provision for the preparation of fuels for use in the experiments, though not for their purification and recovery. Plutonium nitrate solutions are stored in seven slab-shaped tanks having a total capacity of 550 litres. These are independently valved, permitting solutions of several concentrations to be stored, but are all connected to a common mixing tank in which solution for a critical experiment is prepared. The latter is also connected to a continuous steam-heated evaporator in the form of a titanium cylinder, having a throughput of 5 litres/hr, and to two diluent tanks holding dilute nitric acid and condensate water. A solution of any desired concentration up to about 500 g Pu/litre can thus be prepared in the mixing tank, after which it is transferred to a holding tank which supplies the critical assembly apparatus, leaving the mixing tank and other vessels available to carry out further processing. Solution returned from an experiment is passed directly to the mixing tank and thence to one of the stock tanks. Mixing can be effected in all tanks by compressed air sparge and all tanks can be independently sampled for analysis. Level indication is by sight-glass. All transfers other than to and from the critical assembly are by the application of vacuum; transfer to the assembly

apparatus takes place in two stages, first through a service plug in the cell shield to a small intermediate tank, and thence to the core tank itself; both these transfers are by air-operated diaphragm pumps.

Equipment for the preparation of solid fuel tablets of plutonium and moderator is set up in a glove-box line close to the cell entrance. This includes balances and rotary mixers for preparing homogeneous dispersions of plutonium oxide and polyethylene powder, small hydraulic presses, and provisions for packing the pressed tablets in unsealed boxes and for the external decontamination of these boxes. Steam-heated and water-cooled dies of up to 2 in. square section have been used in the presses. Refabrication of the tablets by diluting with additional polythene is carried out in a further glove-box containing a heated extrusion press, granulator and grinder, for reducing the tablets successively to thin rods, chips and powder.

A uranium processing laboratory is available to serve all three uranium assembly cells, though it has no direct pipeline connexions to any of them. This laboratory contains two batch evaporators having a total throughput of 4 litres/hr and which are suitable for uranyl fluoride solutions of all enrichments. Facilities for the recovery of some residues, tissues, etc., are available and two glove-boxes are equipped for the conversion of solid mixtures of uranium tetrafluoride and paraffin wax (used as homogeneous briquettes in critical experiments at low H/U ratios) to uranyl nitrate solutions.

EQUIPMENT FOR CRITICALITY EXPERIMENTS

The critical assembly rigs in use in the United Kingdom can be divided into two main classes, according to whether the fuel and reflector materials are both solid or whether one at least is in liquid form. The two classes differ markedly in their design, experimental use and safety features and are described separately. Attempts have been made, however, to standardize as much of the equipment as possible, particularly that used for measurement and control, and this common equipment is considered first. The main characteristics and uses of the various rigs of both types are summarized in Tables III and IV.

General Design of Critical Assemblies

A critical assembly rig consists essentially of the following basic features:

- a) A means of supporting or containing the fuel material and its reflector (if any);
- b) Some means, closely controlled and readily reversible at all times, of increasing the reactivity of the system;
- c) A means of measuring the 'dependent variable' by which the reactivity is controlled;
- d) Equipment for monitoring the reactivity of the system;
- e) One or more shut-down devices, of the highest possible reliability, capable of reducing the reactivity into the subcritical regions in all eventualities.

Of these, items (a), (b), (c) and (e) are peculiar to each particular rig, though much can be done to standardize the control and measuring equipment and the system for actuating the shut-down devices. Item (d), the reactivity monitoring equipment, can be standardized to a very large extent and will be considered first.

The basic method, used with all the assemblies, of monitoring the reactivity during an approach to criticality is by the response of boron trifluoride-filled proportional counters to a neutron source placed within or close to the core. The BF_3 counter tubes are used either as Hanson and McKibben 'long' counters or are inserted into the reflector of the assembly; counters are not normally used inside the core owing to the need to preserve the clean geometry of the latter. Pulses from these counters are fed via amplifiers to linear ratemeters equipped with adjustable trip relays (which actuate the shut-down devices) and also to scalars for the accurate measurement of the relative neutron multiplication during an approach to criticality.

A minimum of three BF_3 counting channels is provided in all experiments, partly to increase the reliability of trip actuation but more to avoid the need to interrupt an experiment should a channel become 'noisy' or prove insensitive to the reactivity of the system. The use of several channels also improves the accuracy of the estimate of the critical size of a system which cannot be taken as far as the critical point. It has been found expedient at Dounreay to employ at least five BF_3 pulse channels, particularly when working with vessels of complex shape or when a high flux level is to be reached. In the latter circumstance it is often necessary to cut out one or more of the channels in the course of an experiment, though it is not the practice to use fewer than two BF_3 channels and an automatic shut-down is brought about if any attempt is made to cut out all of them.

Unless a system has a high internal production of neutrons, as from spontaneous fission or an (α, n) reaction, the presence of a neutron source is essential to the safety of an experiment. When the critical point is to be found by extrapolation from subcritical multiplications, a 'mock fission' source is used in a fixed location as near as possible to the centre of the fully assembled system. The correction to be applied to the measured critical mass to take account of the source cavity must then be found by a subsidiary 'material replacement' experiment. In experiments intended to attain criticality, the source must be removable (by remote control), though its position and emission spectrum are less important. At Dounreay, Po — Be sources of 10^7 n/s yield are used, the normal working position being about 5 cm outside the core surface.

Several methods have been used for withdrawing the source when near to the critical point, the two most convenient being a pneumatic tube and a system of cable control. Both methods are flexible and can be used to bring the source quite close to the core without impairing its geometry. The pneumatic tube is the more rapid and can easily be arranged to transport the source far from the assembly; the cable system is slower but more positive in operation and a special container, shielded by cadmium and wax, for example, must be provided to screen the source when it is withdrawn from the assembly. Whatever method is used, there must be a positive indication in the control room whenever the source is remote from the core. A continuous indication of source position is an advantage and can be provided by a synchro geared to the cable drive.

Additional radiation detectors are used at Dounreay with systems which are to be made critical ⁽⁵⁾. These normally include two argon-filled ionization chambers (Type TPA) and one or more BF_3 -filled chambers (Type RC-1). The former feed linear amplifiers provided with high and low current trips, and at least one of these channels must be operative at all times. The BF_3

chambers feed logarithmic amplifiers and period meters and three such channels are used in all experiments on plutonium assemblies; these are arranged to give an excess reactivity trip on a two-out-of-three basis when the doubling time falls below five seconds. Period meters are also occasionally used in conjunction with BF_3 pulse counters but have proved unsuitable for trip initiation. Fission counters, coated with U 235, U 238 and Pu 239, are used for special purposes, notably spectral index and fast fission factor measurements, but are not used for control of the assemblies.

In addition to the nuclear instrumentation, the control circuitry of the assembly machines has been standardized to a useful extent in the two laboratories. At Aldermaston a single control desk serves all three machines, a particular area of the desk being used for each one (Figure 5). Each machine also has its local control panel in the cell which can be used for setting-up purposes and which is rendered inoperative by a 'remote/local' key during active runs. At Dounreay, identical relay boxes and 'jumper panels' of modular construction are installed as permanent features of each control room. The rig control panels on the control desk consist of nothing more than switches and indicator lights, all the required control-operations, interlocks and sequencing being provided by cross-connections at the jumper panel. The system has proved remarkably versatile and trouble-free and all

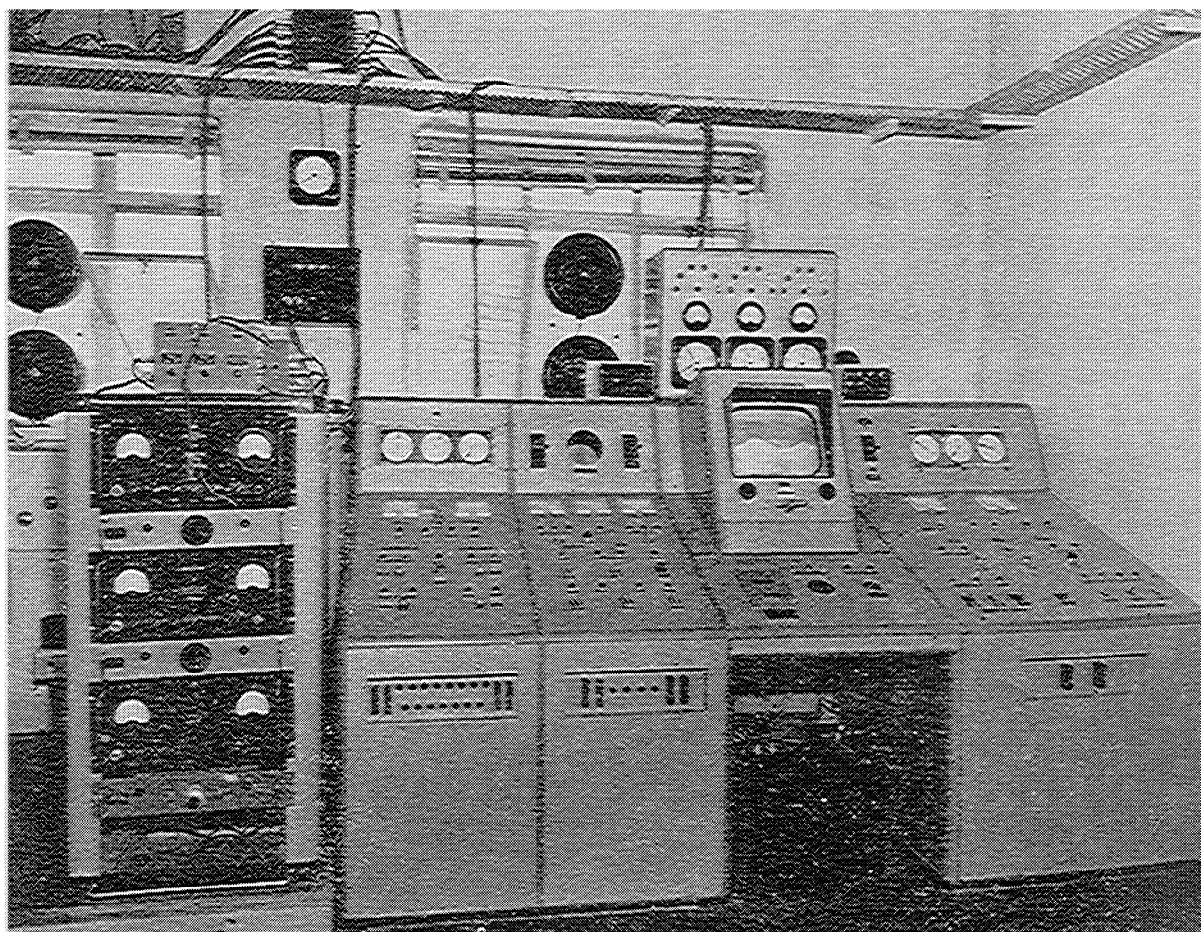


Figure 5. *Main control of the Aldermaston critical assembly laboratory.*

the control facilities for an entirely new experiment can be set up and tested in a few hours, while the diagnosis and cure of electrical faults has been much accelerated.

Machines for Experiments on Solid Systems

Four assembly machines are in current use for experiments on entirely solid systems; their principal features are given in Table III. Two of these, ERIC (Figure 6) and ATLAS (Figure 7), are at Aldermaston and have been in use in one form or another since 1952; the others, PUMA (Figure 8 and TESSIE (Figure 9), are at Dounreay and were installed in 1959 and 1960 respectively. All four machines are essentially similar in that, on each, an

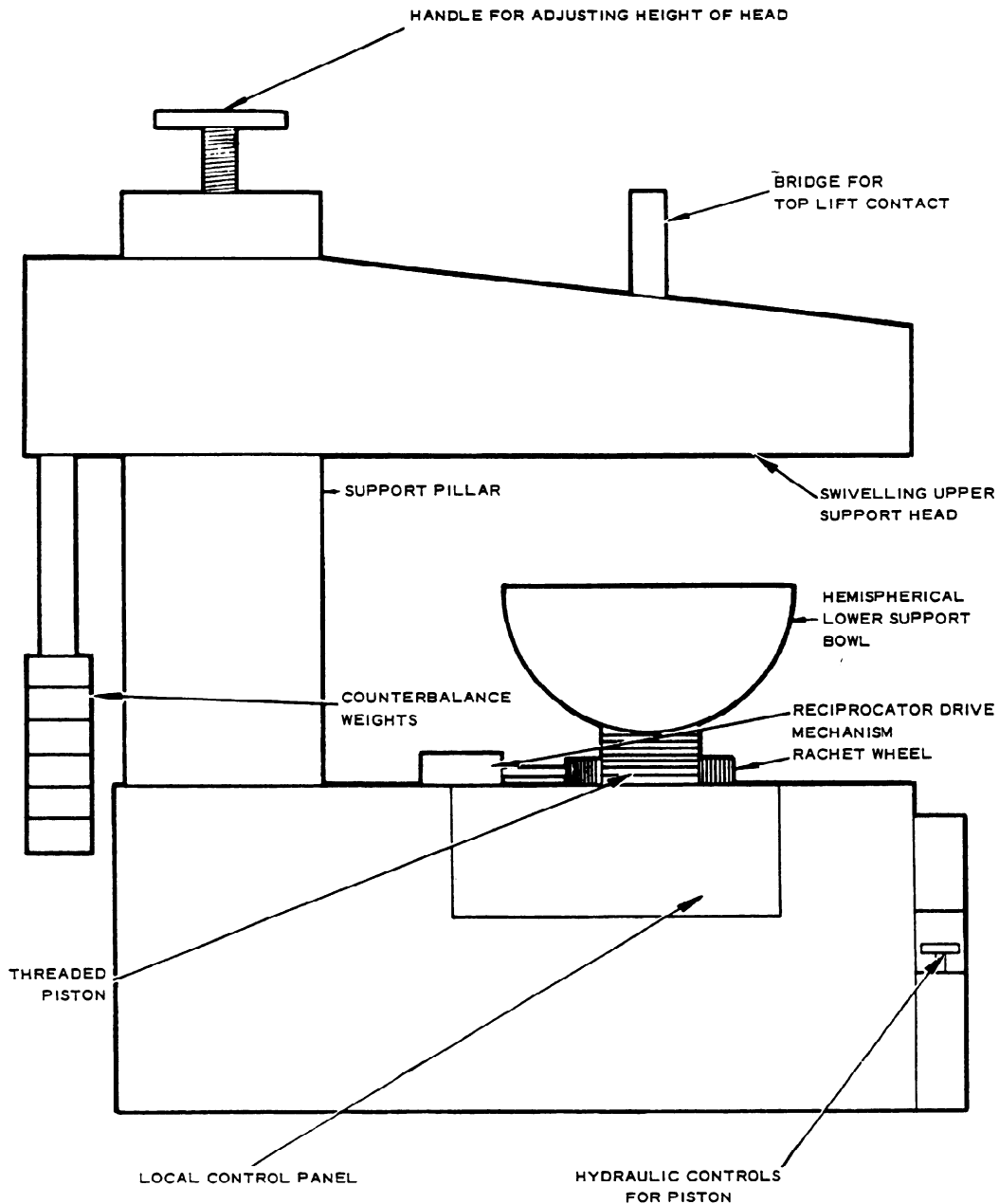


Figure 6a. *The vertical critical assembly machine ERIC (not to scale).*

TABLE III. CHARACTERISTICS AND USES OF UNITED KINGDOM CRITICAL ASSEMBLY MACHINES
MACHINES FOR ENTIRELY SOLID SYSTEMS

Designation	ERIC	ATLAS	PUMA	TESSIE
Location	Aldermaston	Aldermaston	Dounreay (Cell 4)	Dounreay (Cell 3)
Date of first operation.....	1952	1952	Nov. 1960	Nov. 1959
Illustrations	Figure 6	Figure 7	Figure 8	Figures 9 and 15
<i>Principal Characteristics:</i>				
Basis of design.....	Vertical	Vertical	Horizontal	Horizontal
Basis of control.....	Movement of lower table	Movement of lower table	Movement of both tables	Movement of both tables
Basis of shut-down	Physical disassembly	Physical disassembly	Physical disassembly	Physical disassembly
Capacity: load (total)	0.25 ton	5 tons	1 ton	20 tons
size (total)	18 in. dia.	5 ft dia.	3 x 3 x 6 ft	6 x 6 x 10 ft
Max. separation of platforms.....	15 in.	68 in.	40 in.	74 in.
<i>Control Mechanisms (moving table):</i>				
Type of drive	Screw jack, with ratchet nut rotated by hydraulic reciprocator	Hydraulic ram, with forward motion limited by 3 lead screws driven by 'Varimag' motor	Lead screw, rotated by 1 of 3 constant speed electric motors	Lead-screw, rotated by 1 of 4 constant speed electric motors
Range of travel	15 in.	68 in.	30 in.	60 in.
Forward speeds (continuous): fast	0.4 in./min	4.5 in./min	3.0 in./min	17 in./min
intermediate (if any)	Continuously variable	Continuously variable	—	3.15 in./min
slow	Zero	0.075 in./min	a) 0.125 in./min b) 0.095 c) 0.040 d) 0.028	a) 0.63 in./min b) 0.38 c) 0.20 d) 0.12
Availability of forward speeds: fast	—	—	30 to 2 in.	60 to 20 in.
(for table separations) intermediate (if any)	All platform separations	All platform separations	—	60 to 4 in.
(adjustable settings) slow	0.001 in./stroke	—	All separations	All separations
Forward motion - fine adjustment	No steady speed	420 in./min	0.001 in./stroke	0.005/0.0025 in./stroke
Reverse speed (continuous)	None	None	3.0 in./min	17 in./min
Reverse motion - fine adjustment	—	—	0.001 in./stroke	0.005/0.0025 in./stroke
<i>Control Mechanisms (fixed table):</i>				
Type of drive	None	None	Pneumatic ram (oil-damped), hydraulic return buffer	Hydraulic ram, with hydraulic return buffer
Range of travel	Manual adjustment	Fixed platform	12 in.	14 in.
<i>Shut-down Mechanisms:</i>				
Number	One	One	Two	Two
Primary: type	(1) Release of lower platform, with initial free fall under gravity	—	Release of 'fixed' platform with initial acceleration of 0.1 g down 5° slope	—
delay time after trip	135 ms	90 ms	150 ms	—
free travel distance	3 in. (vertical)	—	2 in. (inclined)	4 in. (inclined)
retardation	Hydraulic damping over final 12 in. of travel	Hydraulic damping over final 15 in. of travel	Hydraulic damping over final 10 in. of travel	Gradual closure of oil return valve
Secondary: type	None	None	Reversal of motion of 'moving' platform, driven by either a.c. mains or d.c. battery supplies	—
<i>Measurement of Table Separation:</i>				
Method of indication	Synchros (3) geared to screw-jack	Synchros (3) geared to lead screws	Metal scale and vernier, viewed by TV (12 in. lens)	Metal scale and vernier, viewed by TV (12 in. lens)
Error at small separations	0.003 in. max.	—	0.001 in.	0.002 in.
Reproducibility	0.001 in.	0.002 in.	—	—
<i>Typical Experimental Systems:</i>				
Material and nature of core.....	Small assemblies of Pu or U 235 metal parts	Large U 235 metal assemblies, solid mixtures of enriched UO ₂ and wax moderator	Solid mixtures of plutonium oxide and plastic moderator	Solid mixtures of low enrichment UF ₄ and paraffin wax moderator (see also SIRIUS - Table IV)
Peak neutron flux (n/cm ² /s).....	10 ⁴	10 ⁴	10 ⁷	10 ⁴
Max. thermal power	~ 0.1 W	~ 0.1 W	10 W	5 kW

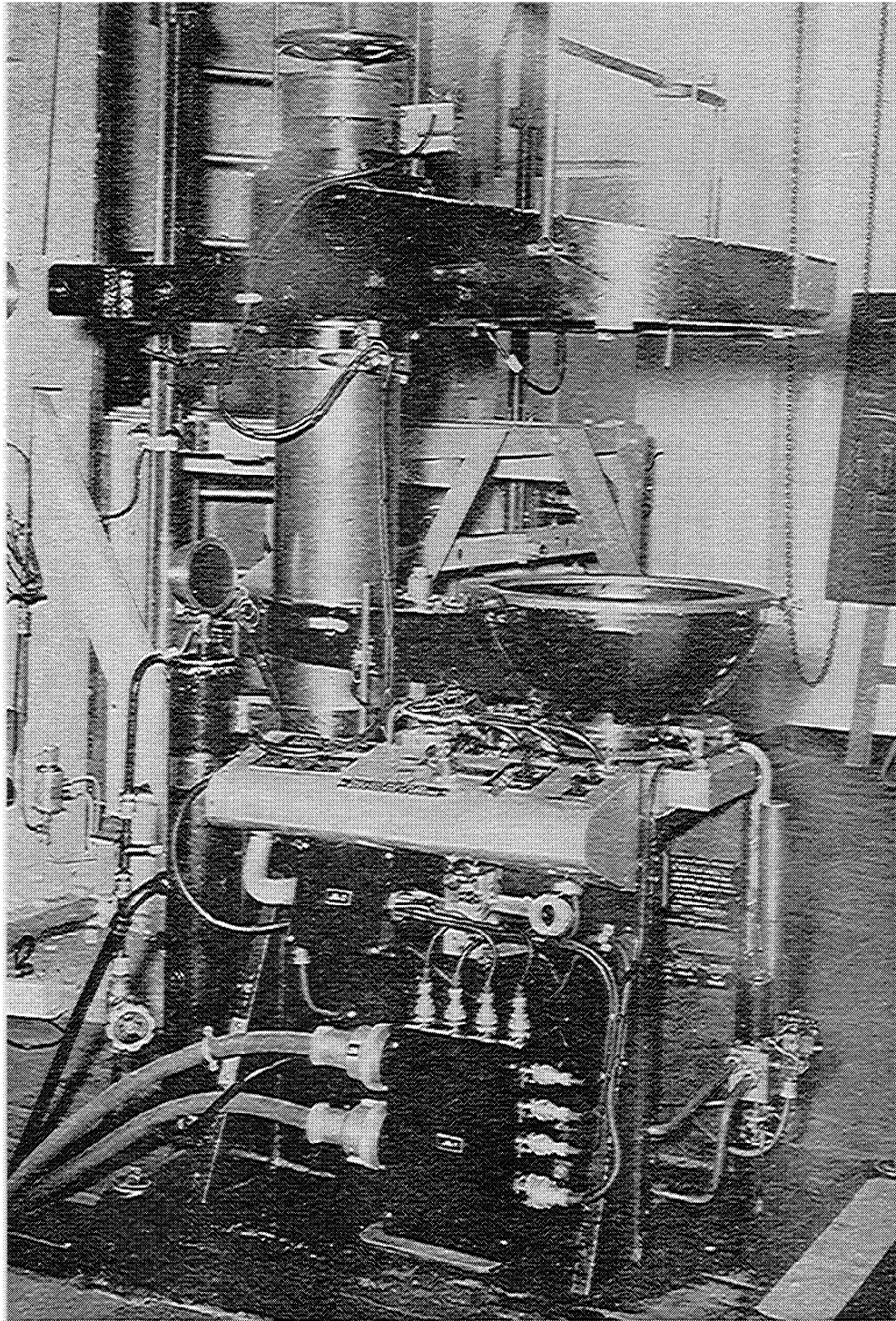
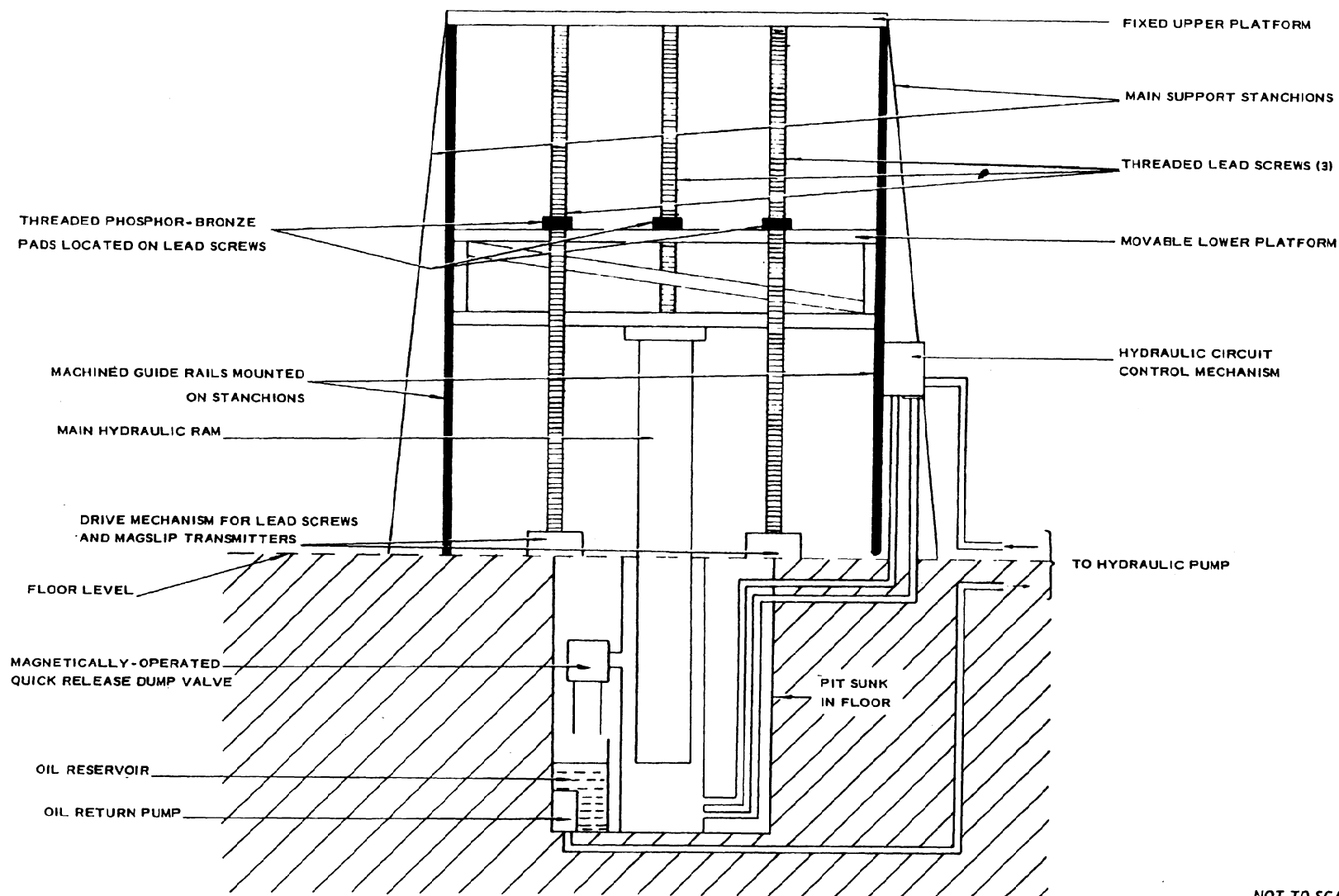


Figure 6b. *The vertical critical assembly machine ERIC.*



NOT TO SCALE

Figure 7a. The ATLAS high capacity vertical assembly machine. (side elevation).

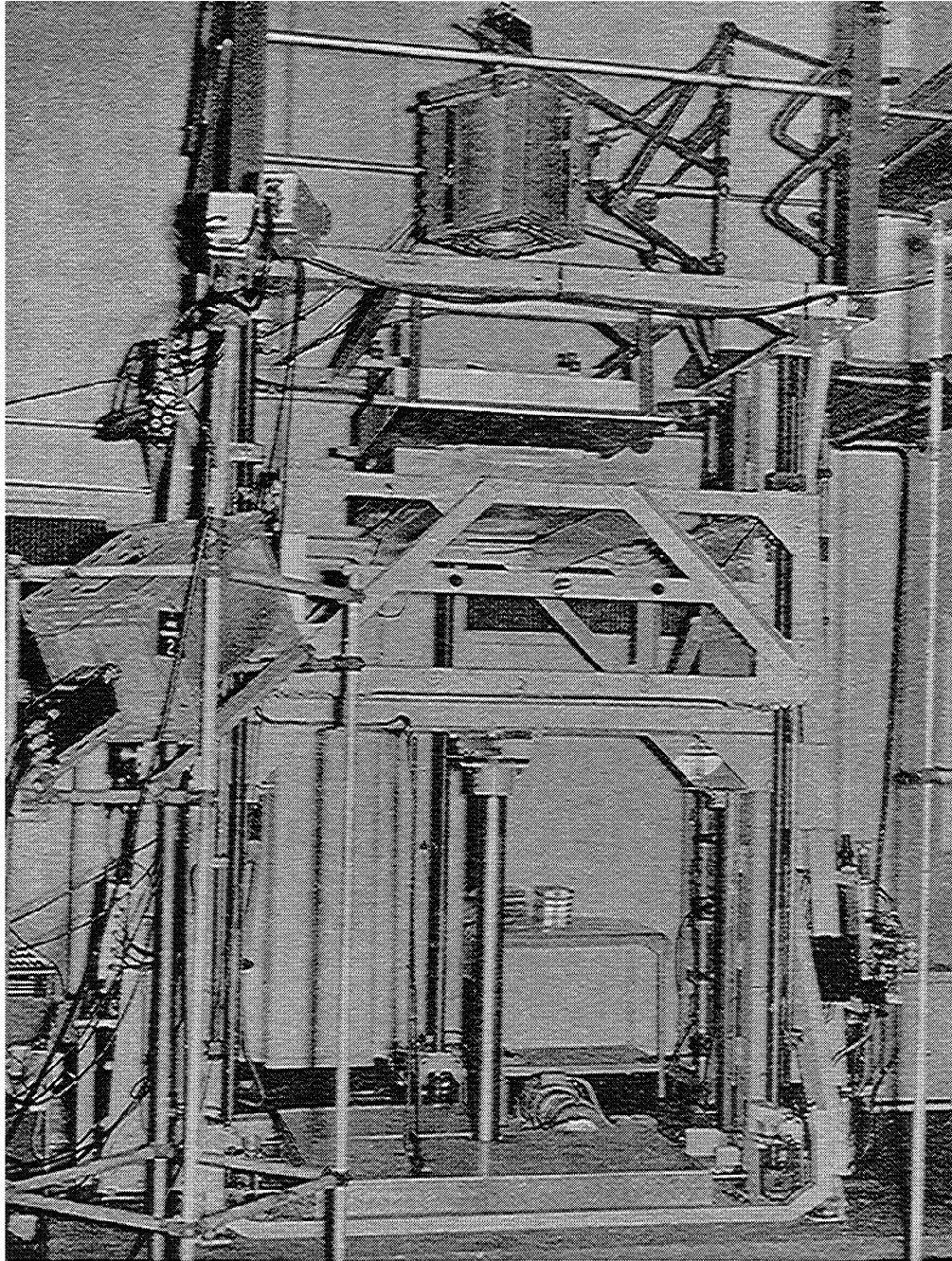


Figure 7b. *The ATLAS high capacity vertical assembly machine.*

assembly is first built by hand in two parts, one of which is then driven towards the other under remote control. No control or safety rods are employed with any of them, safety being dependent primarily on the limited speed of approach of one part of the assembly to the other and on the rapid separation of the two parts in the event of a trip. Only a single shut-down mechanism is provided on each: the rapid separation of the two parts under gravity.

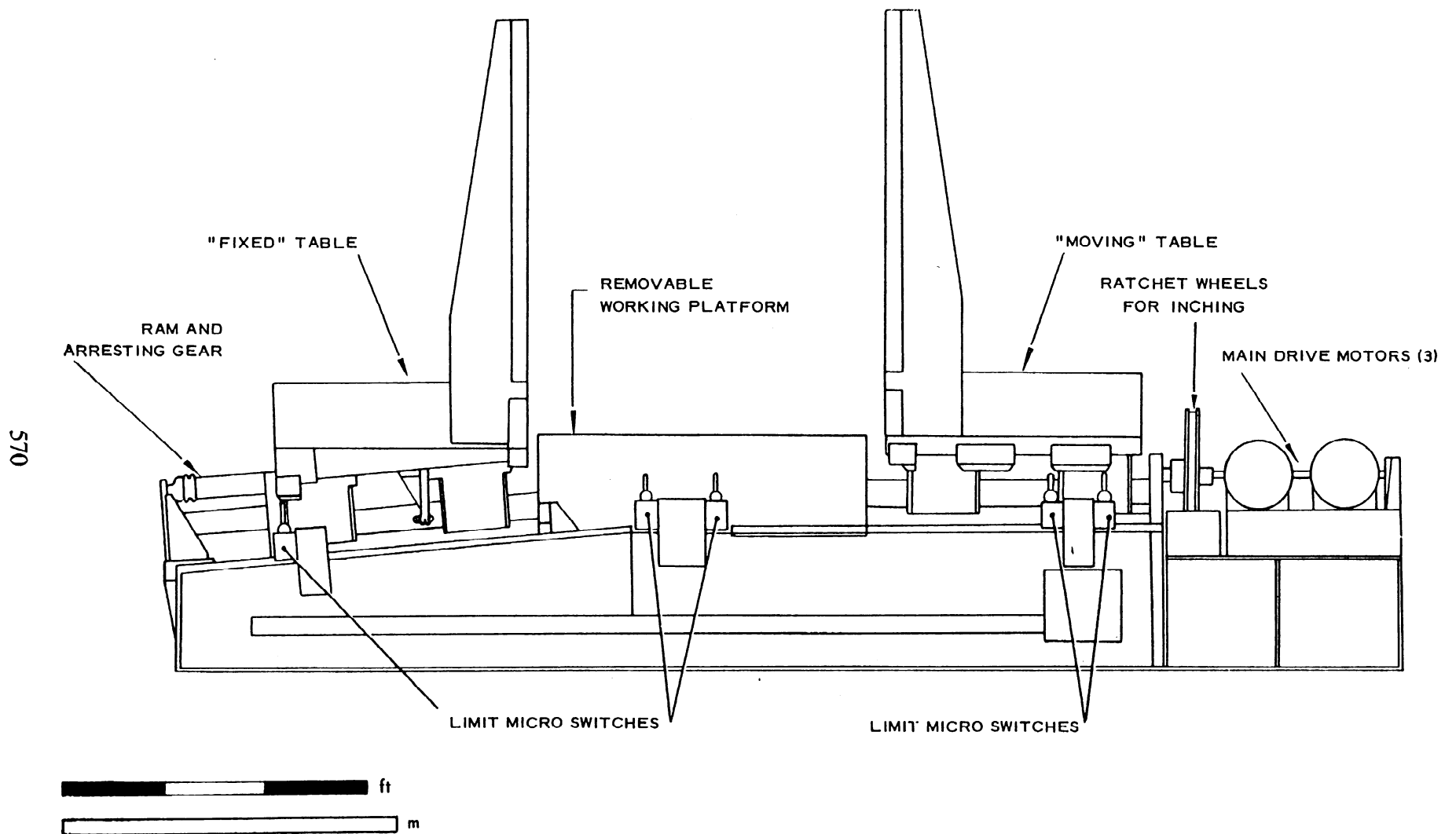


Figure 8. Elevation of PUMA assembly machine, showing tables in retracted positions.

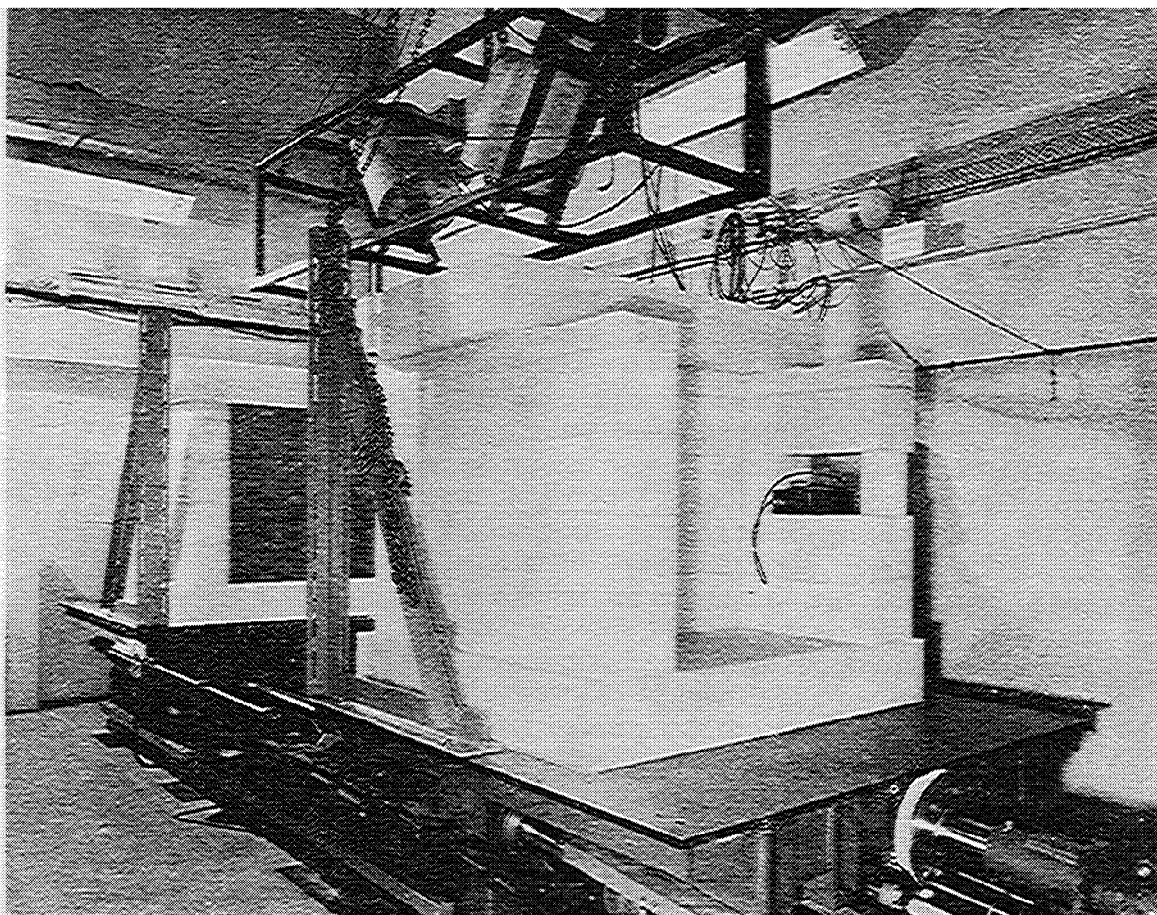


Figure 9. *The TESSIE horizontal assembly machine, showing a cubical core of low enrichment uranium tetrafluoride and paraffin wax mixture with thick polyethylene reflector.*

The two Aldermaston machines are characterized by the movement of a lower platform vertically upwards towards a fixed upper one, the lower platform being able to fall away freely under gravity in the event of a trip. In the Dounreay machines assembly takes place in a horizontal direction and both platforms can move, though the movement of one serves only to disassemble the system on trip. The two types of machine are largely complementary in function and it is an advantage to be able to select whichever is most appropriate for a particular experiment.

The vertical machines are especially suitable for high density systems where external clamping arrangements are undesirable or are difficult to provide; they have the merit of the very effective shut-down action which the free fall of the lower platform makes possible. It is fairly easy to ensure accurate mating and alignment of the two halves. The symmetry about a vertical axis is convenient in work on heterogeneous systems and it is somewhat easier than the horizontal arrangement for demonstrating the safety of a subsequent stage in an experiment. It is also of great value in some interaction studies on mixed systems where a liquid reflector or a tank of fissile solution is to be brought towards a solid core or reflector. The vertical arrangement

has the disadvantage that the upper part of all but the smallest assemblies requires to be supported by a membrane of foreign material, the effect of which must be found in a tedious and sometimes unreliable subsidiary experiment. Care must be taken whenever additions or alterations are made to the upper part of the assembly, owing to the risk of fuel or reflector material falling onto the lower part.

The horizontal design of the machine eliminates the need for any supporting plate inside the core, making it possible to measure the critical sizes of cores in the absence of internal perturbations. Its main disadvantage is the difficulty of providing a rapid and fail-safe disassembly mechanism. On both the Dounreay machines, one of the tables is mounted on a sloping track, down which the table slides with an acceleration of about 0.1 g in the event of a trip; although reliable, this arrangement does not provide as rapid a reduction in reactivity as might be desired. More rapid separation can be achieved by some form of energy storage such as springs, suspended weights or compressed air cylinders, but only at the cost of securely clamping the assembly to the table. Even in the sloping track design, external clamps are often needed to maintain the stability of unreflected assemblies and allowance has to be made for unwanted neutron reflection from the clamping structure. Provision has to be made, also, to absorb the kinetic energy of the moving platform after disassembly. The horizontal design has proved convenient for experiments requiring frequent changes to the core geometry and where ready access to the core centre is needed for flux distribution and spectrum measurements, material replacement tests, etc; it is less satisfactory for work with liquid reflectors or where the entire reflector has to be varied in nature or thickness, owing to the difficulty of access to the underside of the core. A high load capacity is more easily achieved with the horizontal design.

Summarizing, the horizontal type of machine is thought to be somewhat more versatile and convenient in operation than the vertical arrangement. It would probably be slower in regaining a subcritical condition in the event of a reactivity burst, but does not demand such close administrative control of loading or core changes during normal use. The critical parameters of cores unperturbed by the presence of foreign materials or voids can be measured directly on a horizontal machine; experiments on bare cores free from unwanted neutron reflection are more readily performed in a vertical arrangement.

The smaller vertical machine, ERIC (Figure 6), is used almost exclusively for experiments on small metal assemblies, usually of high density and simple shape. It is suitable for systems, either bare or reflected, up to 18 in. dia. and 500 lb weight. The upper part of a proposed assembly is attached to a light alloy frame, adjustable in height but fixed during a critical approach. This frame has a limited amount of side float and is equipped with levelling screws to ensure correct mating, without risk of jamming, of components during the final stages of assembly. A counterbalance weight is used to reduce distortion of the machine structure when carrying heavy loads on the upper platform. The lower section is carried on a screw-jack capable of very slow and precise upward movement, the screw being raised or lowered by a ratchet nut, itself turned by a hydraulic reciprocator which can be operated either in single strokes (giving a movement of the load of 0.001 in.) or continuously at speeds up to 400 strokes/min (0.4 in./min). The precision of the screw and nut is such that the actual position of the platform lies within 0.0008 in. of the calculated position over the whole 15 in. range of travel and is repro-

ducible to within 0.0001 in. The separation of the tables is displayed, both on the machine and in the control room, by synchros geared to the screw-jack and having a maximum following error of 0.001 in. Transmitter-receiver synchronization is checked by electrical contacts on the screw-jack at 0.1-in. intervals. Rapid fall of the lower platform on trip is achieved by disengaging the nut and screw from the driving mechanism; the release action is fail-safe and is assisted by the weight of the load; the total release time is about 135 ms, after which the platform falls freely for 3 in. and is subsequently brought gradually to rest over the remaining 12 in. by a hydraulic damper.

The larger vertical machine, ATLAS (Figure 7), has a load capacity of 2.5 tons per platform and can accept assemblies up to about 5 ft dia. The main structure consists of two substantial 10 ft high stanchions carrying the fixed upper platform. The lower platform travels vertically within guides on the main stanchions and is located by roller bearings over its full travel of 68 in., its weight and that of the load being supported by a 4 in. dia. hydraulic ram in a well below the machine. Precise control of the movement of the lower platform is provided by three vertical lead screws, driven simultaneously by a 'Varimag' electric motor and carrying threaded pads to which limit switches are fixed. The platform can rise freely until it reaches the pads, after which contact between them is maintained automatically throughout the upward movement. The speed of vertical movement can be varied continuously from 0.075 to 4.5 in./min. The position of the three pads, and hence of the platform, is displayed by synchros geared to the lead screws and readable to 0.002 in.; the position of the platform when not in contact with the pads is adjustable, by control of the oil flow to the ram, to better than 0.1 in. On trip, a quick-release dump valve in the hydraulic circuit allows the platform to fall at about 7 in./s, until it is brought smoothly to rest over the last 15 in. of travel by the gradual closure of the oil dump valve.

The two horizontal machines, TESSIE and PUMA, are similar in design, differing mainly in size and hence in their load capacity and fineness of control. The smaller of the two, PUMA, is shown in Figure 8 and is intended primarily for experiments on solid moderated systems of plutonium or highly-enriched uranium. It has a load-bearing capacity, without more than 0.005 in. distortion of the structure, of 500 lb per table and can accept assemblies having dimensions up to $3 \times 3 \times 6$ ft overall, including reflector. The two tables are each carried on four recirculating ball bushings running on two parallel round bars, an arrangement giving extremely free movement. The bars supporting one table are inclined at an angle of 5° to the horizontal. This table is pushed by a pneumatic piston through a distance of 12 in. to its normal operating position at the top of the 5° slope, where it is held by an electromagnet. The other table is driven horizontally towards the other from its maximum distance away of 30 in., first at a 'fast' speed of 3 in./min and later at one of four pre-selected 'slow' speeds within the range 0.028 — 0.12 in./min; a pre-set electrical cut-out, adjustable in position, prevents use of the fast speed at separations smaller than a few inches. Fine adjustment of the table position can also be made by an inching mechanism, consisting of a pneumatically driven pawl which engages a ratchet wheel on the lead screw; two such mechanisms are provided, allowing the table to be either advanced or retracted by 0.001 in./stroke. The separation of the two tables is indicated directly by a metal scale and vernier, visible on the machine itself and also in the control room over a closed circuit television link. The separa-

tion can be read, using a 12-in. camera lens, to within 0.001 in. and is reproducible to this accuracy up to separations of several inches.

Rapid disassembly of PUMA, on receipt of a trip signal, is brought about by the movement of both tables. The normally fixed table is released by its magnet after about 150 ms from trip initiation, accelerates freely under a 10 % component of gravity up to a separation of 2 in. and is subsequently brought smoothly to rest by a hydraulic buffer after travelling its full distance within 6 s. The reverse movement of the other table (at 3 in./min) is scarcely less reliable, although dependent on electrical supplies; it occurs provided that *either* the 240 V a.c. mains *or* a 24 V d.c. battery supply to an additional motor is maintained.

The TESSIE horizontal assembly machine (Figure 9) is suitable for systems up to 20 tons in total weight and several cubic yards in volume. Its general structure and control mechanisms resemble those of PUMA very closely. The fixed table is raised by a hydraulic, rather than a pneumatic, piston and is arrested after a trip by the gradual closure of a throttling valve in the oil circuit. The travel of the moving table is 5 ft, and three forward speeds are provided for its control during an approach to criticality. Typical ranges of availability of the speeds are: 17 in./min from 60 to 20 in.; 3.15 in./min from 60 to ; 4 in. and 0.63 in./min (or 0.12 in./min) from 60 in. to zero separation. Forward and reverse inching in steps of 0.005 in. is also provided. The TESSIE machine is used for measurements on homogeneous stacks of low enrichment uranium and moderator mixtures or other large dilute systems, for *ad hoc* experiments on processing plant vessels and for carrying subsidiary experimental rigs used in interaction studies, such as the SIRIUS apparatus described below.

Equipment for Liquid Critical Assembly Experiments

Critical assemblies in which either or both of the core and reflector are in liquid form have the advantage that the liquid level can be used to provide very sensitive control of reactivity. By the same token, dumping the liquid under gravity — especially when this is the core material — can be made to serve as a convenient and highly effective shut-down device. On the other hand, systems using liquid cores are in two respects considerably more troublesome to operate than solid systems: a fairly elaborate solution storage and handling system, preferably including facilities for dilution and evaporation, is needed to supply the fissile core solutions and, where plutonium solutions are concerned, must be provided as a permanent installation; and the need to break fuel lines when changing core vessels retards working owing to the need to follow active handling procedures.

It is a relatively simple matter to vary the moderation of a solution-cored system, at least within the range of chemical solubility; it is very much less easy to change the size of core vessel. In solid systems the reverse obtains, the re-assembly of core components into different core shapes being straightforward, whereas a homogeneous change of moderation necessitates the reprocessing of the entire core. In solution systems, the fuel density is related to the moderation in a definite manner and only elementary precautions need be taken to eliminate voids and maintain homogeneity; in contrast the achievement of densities close to theoretical in solid homogeneous mixtures of fuel and moderator is often difficult. A supercritical excursion in a solution system is demonstrably self-limiting by virtue of the void coefficient of reactivity

for radiolytic gas formation; this is not necessarily so in a moderated solid assembly unless it is initially free from built-in voids.

A number of rigs has been in use at Harwell and Dounreay since 1952 for studies on entirely liquid systems, details of the majority of which are given in Table IV. Three such rigs — PANTHER, PHOENIX and TOAD — are in current operation at Dounreay and are described in this report. Two additional machines (WATERFALL and SIRIUS) are in use for experiments with part-liquid, part-solid systems, and a design study has been completed for a third (SORCERER).

The WATERFALL machine (Figures 10 and 11) installed at Aldermaston, is used to surround small solid cores, usually of metal, by liquid reflectors up to 24 in. dia. The core, previously shown to be subcritical and safe to handle by an experiment on an approach machine, is supported on a light aluminium tube at the centre of a spherical copper vessel. Reflector liquid is pumped from a reservoir into this sphere by a piston pump driven by a second, double-acting piston actuated by oil pressure; the stroke and speed of the latter can be varied so as to insert 'shots' of reflector liquid between 1.6 and 60 cm³ in volume either singly or continuously at speeds from 30 to 200/min. An additional valve allows liquid to be withdrawn from the reflector vessel at the same rates. A trip signal interrupts the power supply to the pump and to a magnetic valve in a large diameter dump pipe at the base of the

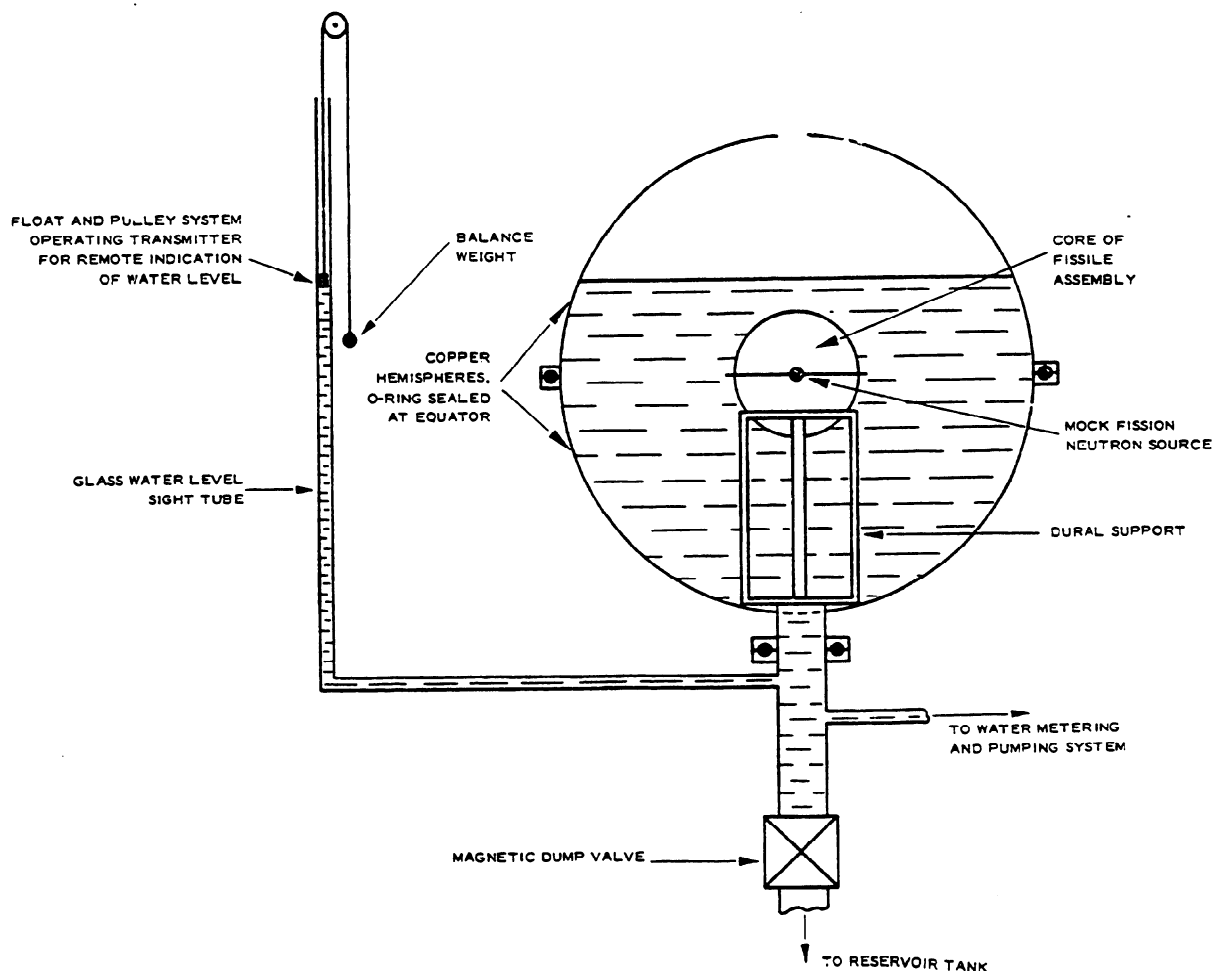


Figure 10. *The WATERFALL critical assembly equipment (vertical section).*

TABLE IV. CHARACTERISTICS AND USES OF UNITED KINGDOM CRITICAL ASSEMBLY MACHINES
EQUIPMENT FOR PARTLY OR WHOLLY LIQUID SYSTEMS

Designation (with earlier designation)	WATERFALL	ZETR-0 (Pu ZETR)	ZETR-1a	ZETR-1b/c	HAZEL (ZETR-II)	PANTHER	TOAD (ZETR-III)	PHOENIX (HAZEL-II)	SIRIUS	SORCERER
Location	Aldermaston	Harwell	Harwell	Dounreay (Cells 1 and 2)	Harwell	Dounreay (Cell 4)	Dounreay (Cell 1)	Dounreay (Cell 1)	Dounreay (Cell 3)	(for Dounreay Cell 1)
Date of first operation	ca. 1954	1952	1955	Aug. 1957	April 1958	1961	1961	July 1960	May 1961	(Design study: 1961)
Date dismantled	—	ca. 1953	1956	Aug. 1960	Sept. 1958	—	—	—	—	Not shown
Illustrations	Figures 10 and 11	Not shown	Not shown	Not shown	Not shown	Figure 12	Not shown	Figure 13	Figure 14	Not shown
<i>Principal Characteristics:</i>										
Core: isotope	U 235 or Pu	Pu	U 233/U 235	U 235	U 235	Pu	U 235	U 235	U 235	U 235
enrichment (%)	Various	—	45	30 or 93	45	—	30	30 or 93	30 or 93	30 or 93
moderator	None	H ₂ O	H ₂ O	H ₂ O or TEP/OK	H ₂ O	H ₂ O	H ₂ O	H ₂ O	H ₂ O	H ₂ O
phys. form	Metal	Solution	Solution	Solution or complex	Solution	Solution	Solution	Solution	Solution	Solution
chem. form	Metal	Nitrate	UO ₂ F ₂	Nitrate or UO ₂ F ₂	UO ₂ F ₂	Nitrate	UO ₂ F ₂	UO ₂ F ₂	UO ₂ F ₂	UO ₂ F ₂
shape	Sphere (cg)	Cylinder	Cylinder	Cylinder (1 or 2-zone)	Cylinder	Cyl./sphere	Cyl./sphere (1,2 or 3-zone)	Cyl./sphere	2 × Slabs (interacting)	Slab
Reflector: material	Water/oil	Water	Water	Water/bare	Graphite	Water/bare	Water/bare	Water/bare	Polythene	Various
coverage	Complete	Radial	Radial	Radial	Radial	Complete/side	Complete/side	Complete/side	All faces	1 or 2 faces
thickness	Inf.	Inf.	Inf.	Inf.	47 cm	Inf.	Inf./various	Inf.	Inf.	Various
Core vessels: material	—	S/steel	S/steel	S/steel	S/steel	Al	Al	S/steel or Al	S/steel	Al
Peak flux (n/cm ² /s)	10 ⁴	10 ⁴	10 ⁴	10 ⁴	10 ⁴	10 ⁴	10 ⁴	10 ⁴	10 ⁴	10 ⁴
Max. thermal power (W)	—	—	—	0.1	1	10	10	100	100	100
<i>Control Mechanisms:</i>										
Core	(Fixed)	Suction	Suction	Suction/Pump	Pump	Pump	Pump	Pump	Pump	Pump
Reflector	Pump	Pump	Pump	Pump	(Fixed)	—	—	—	(Fixed)	(Fixed)
Other	—	—	—	Reflector shield	Reflector shield	—	—	—	Table separation	—
<i>Shut-down Mechanisms:</i>										
Number	One	Two	Two	1 or 3	Two	2 or 3	2, 3 or 4	2 or 3	2 per tank	1 or 2
Primary	Reflector dump	Reflector shield	Reflector shield	Core dump	Core rods (2)	Core dump	Core dump	Core dump	Core dump (2)	Core dump
Secondary	—	Reflector dump	Reflector dump	(Reflector shield)	Reflector shield	(Reflector dump)	(Reflector dump)	(Reflector dump)	Table drop	Reflector drop
Other	—	—	—	(Reflector dump)	—	(Core pump- out)	(Buffer dump; core pump- out)	(Core pump- out)	Table drive	—
<i>Range of Core Vessels:</i>										
Close } Spheres - Number	(Reflector: 24 in. dia.)	—	—	—	—	10	6	1	—	—
gaps } - Diameters (in.)						9 to 38	9 to 22	38		
Close } Iso. Cyls. - Number						3	2	—		
gaps } - Diameters (in.)						8.5 to 12	10 and 12.5	—		
Close } Tall Cyls. - Number		1	2	4	1	5	6	6	—	—
gaps } - Diameters (in.)						5.5 to 9	7 to 10	7.5 to 40		
gaps } - Max. Ht. (in.)						60	30	108		
Close } Squat Cyls. - Number						4	Plus 6 thin re- flector tanks; plus 7 buffer and speci- men cores	—		
gaps } (slabs) - Depths (in.)		—	—	—	—	2.5 to 5		—	4 × 2 slabs	1 slab
gaps } - Area (in.)		—	—	—	—	30 in. dia.		—	1.5 to 4	Up to 18
									48 in. square	48 in. square

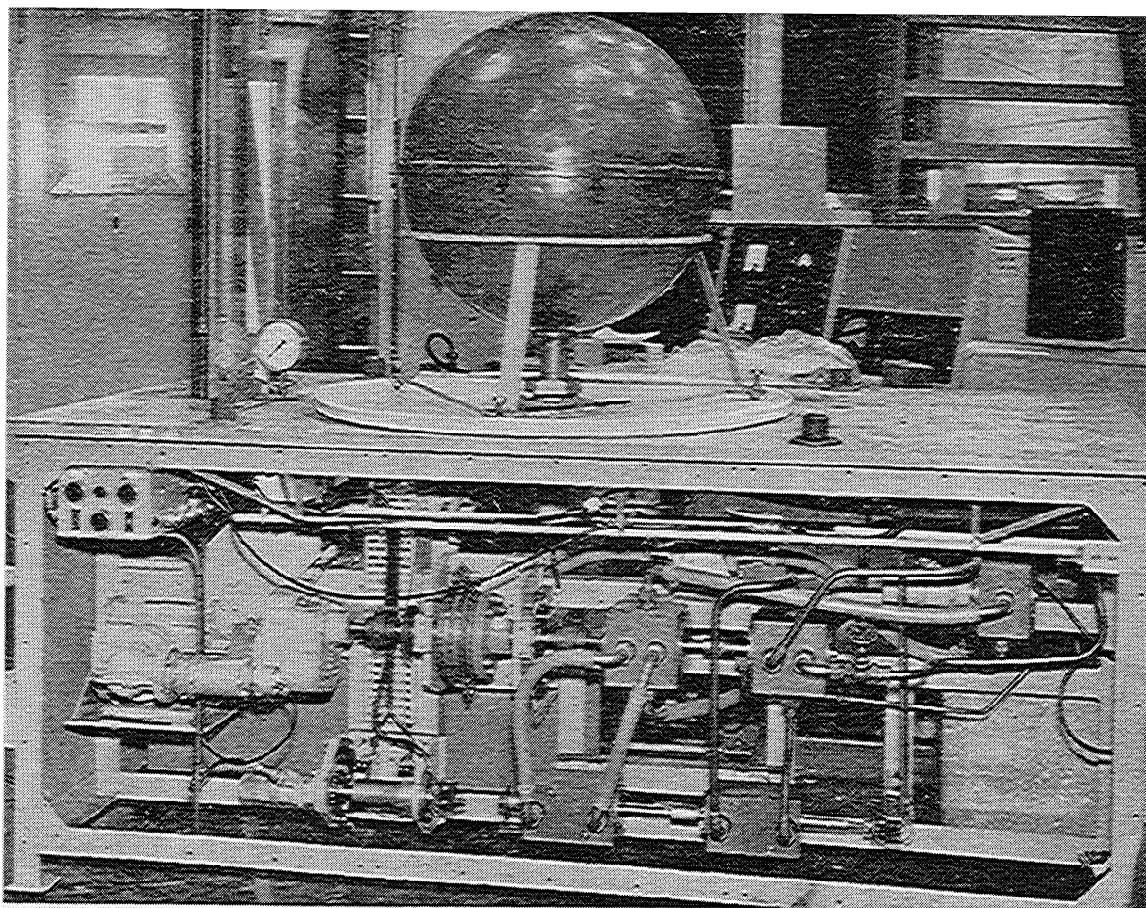


Figure 11. *The WATERFALL critical assembly equipment, viewed from the side.*

reflector tank. The reflector level is indicated locally by a vertical sight glass alongside the machine; a float in this tube, joined to a counterweight by a silk thread passing over the drive pulley of a synchro, transmits this level to the control room with a reproducibility better than 0.02 in. over the full range of 26 in.

The three Dounreay solution rigs are all basically similar, differing mainly in the size range of their core tanks and in the degree of containment. All three are more versatile and more rapid in operation than any of their predecessors. The most recently constructed of these, PANTHER (Figure 12), has been designed to measure the critical parameters of plutonium nitrate solutions, with or without a water reflector, over the whole accessible range of concentrations. It consists essentially of four units: a core tank, interchangeable with others in a comprehensive range of shapes and sizes; a removable cylindrical reflector tank surrounding the core tank; two dump tanks, one for fuel solutions from the core and one for reflector liquid. The whole apparatus, with the exception of the reflector dump tank, is contained in a transparent glove-box equipped with tent flanges to enable personnel to carry out core tank changes and general maintenance. The range of interchangeable core tanks includes ten spheres (9 to 38 in. dia.), three isometric cylinders

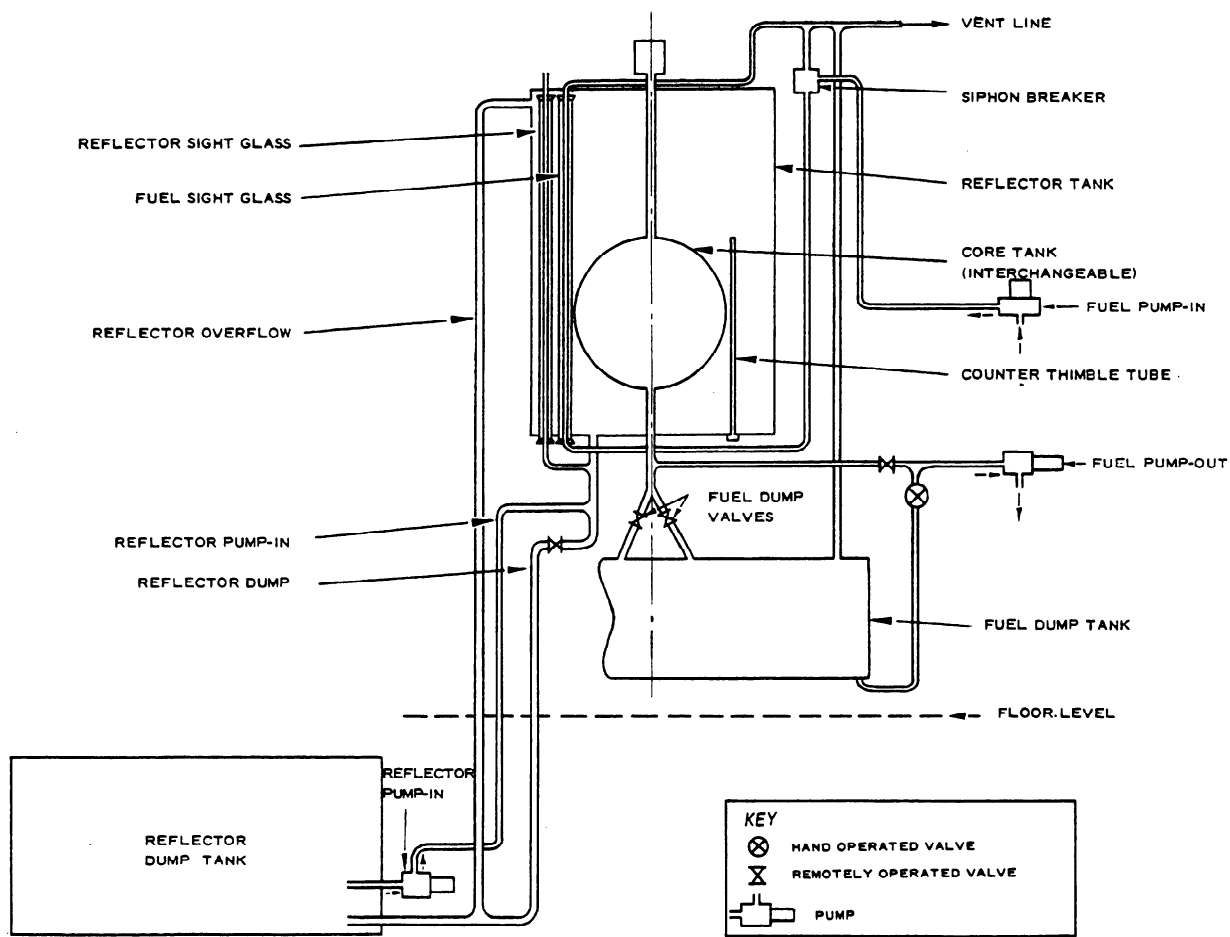


Figure 12. *PANTHER*. A critical assembly apparatus for plutonium solutions.

(8.5 to 12 in. dia.), and four shallow cylinders (30 in. dia. and 2.5 to 5 in. deep), all of which can be fully reflected by water if required. There are, in addition, five tall cylinders (60 in. high and 5.5 to 9 in. dia.) which can be reflected in a radial direction only. The core tanks are of 0.064 in. thick aluminium, protected against attack by the fuel solutions by an epoxy resin lacquer. A vertical pipe at the base of the core tank serves as the normal filling and emptying line and also as a fuel dump pipe through which a portion of the core solution can be rapidly discharged to a geometrically safe vessel in the event of a trip; a similar pipe at the top of the core tank serves as a pressure balance line.

Plutonium nitrate solution is supplied to the *PANTHER* rig from the holding tank of the fuel storage system previously described, in two stages: in the first, a predetermined volume of solution is pumped quite rapidly through the wall of the cell into a 20-litre intermediate vessel inside the cell; in the second stage, this solution is transferred at a predetermined rate into the core tank itself. The two-stage procedure eliminates the need for any direct connection between an 'unsafe' vessel (the core tank) and a virtually unlimited source of fuel, thereby providing protection against over-running of the pump; it also enables the cell to be completely sealed whenever reactivity is added to the system. The return of solutions from the core tank to storage is effec-

ted in a single operation. Reflector water is pumped, when required, from a dump tank in a pit below the rig into a large cylindrical vessel surrounding the core. The levels of fuel and reflector liquids can be read locally by sight glasses and in the control room over a closed-circuit television link with an accuracy, after previous calibration, of ± 0.020 in.; complete filling of the spherical and closed cylindrical core tanks is also detected by electrical contact probes.

In the absence of a liquid reflector, rapid shut-down of PANTHER, as also of TOAD and PHOENIX, is entirely dependent on a single safety mechanism: the removal of fuel solution by dumping under gravity. To enhance the reliability of this action, two parallel dump lines, each closed by a large diameter, air-operated diaphragm valve controlled by its own trip-responding circuit, are provided. In addition, duplicate electrical contact probes ensure that the dump tank is empty whenever reactivity is added to the system. It is not always convenient, nor is it necessary, to provide dump tank capacity for the entire contents of the core vessel. The principle guiding the design of a dump tank is that it shall, by accepting at least 20 % of the volume of the largest core tank, enable reactivity to be reduced at a rate approaching several per cent k/s up to a total of a few per cent in k; further reduction in reactivity then continues at a slower rate by the pumped removal of solutions from the dump tank until the system is empty. The gravity flow of fuel by dumping is, as nearly as can be contrived, proof against failure. Its continued removal by pumping is somewhat less reliable, being dependent on electrical supplies to a pump, though these are duplicated. In experiments employing a liquid reflector, the latter is also dumped under gravity in the event of a trip. For convenience, the level of the reflector trip is usually set below that of the core trip to permit a quicker resumption of an approach to criticality should the trip have some trivial origin such as counter noise. The reflector dump system is not duplicated, though, to give a comparable rate of reactivity reduction, it must be of larger flow capacity than that serving the core. The dump tank for the reflector is also the storage tank and can thus accept the whole volume of reflector liquid.

The TOAD liquid critical assembly equipment closely resembles PANTHER in its design and method of operation. It is intended primarily for basic criticality studies on fairly small vessels containing uranyl fluoride solutions of medium or high U 235 isotopic content; separate containment of the rig has not therefore been considered necessary. The range of fourteen interchangeable core tanks includes spheres, isometric cylinders and tall cylinders up to a maximum core diameter of 22 in. (see Table IV). In addition, seven special cylindrical tanks are available for studies on two- and three-region cores, including replacement experiments in which the reactivity of a specially prepared test sample can be compared with that of a void. This latter facility has been included as a convenient if somewhat approximate means of assessing the criticality of 'awkward' materials such as wet powders, curds, sludges, and solutions containing dispersed or lumped neutron poisons. The provision of three core regions allows the neutron spectrum of the test specimen to be roughly matched with that of the main or 'driver' part of the core by a 'buffer' region of similar composition to the specimen itself. Six further tanks are available for experiments on tall cylinders having thin or nominal water reflectors of 0.5, 1 and 2 in. radial thickness; these are intended to provide critical data applicable to process plant situations where

the neutron reflection, although not negligible, is demonstrably less than that in a fully-reflected environment. All the TOAD core tanks are of aluminium alloy, usually 0.128 in. thick. The fuel and reflector dump systems are similar to those of PANTHER, with the addition of a third dump system to serve the buffer region of the core when this is in use. The levels of liquids in the three core regions and the reflector are reproduced in parallel sight glasses within the field of a single television camera and can be read in the control room to an accuracy of ± 0.030 in.

The PHOENIX equipment (Figure 13) is used for critical mass studies on enriched uranium solutions in vessels of considerable diameter or height; it is thus complementary in scope to TOAD and resembles it in design and operation. The range of core tanks includes tall or 'near-infinite' cylinders (9 ft high and 7 to 10 in. dia.), large cylinders (up to at least 40 in. dia.) for studies on shallow slabs and on low concentration systems, and a 38 in. dia. sphere. The reflector tank can be readily removed, making the equipment suitable for examining the effects of *ad hoc* plant conditions, such as reflection by persons or by walls or other building structures. The basic equipment can also be used to operate a specimen of a proposed process vessel as a solution-filled critical assembly and thus to give direct information on the nuclear safety of such vessels.

An apparatus has recently been constructed at Dounreay for measuring the degree of nuclear interaction between vessels containing solutions of U 235. In its initial form the equipment, designated SIRIUS (Figure 14), consists of two parallel slab-shaped tanks, each mounted vertically on one of the platforms of the TESSIE assembly machine (Figure 9). Pairs of tanks of various internal thicknesses between 1.5 and 4 in.) are available; they are 4 ft wide and are normally filled with solution to a depth of 4 ft. The primary purpose of the experiment is to measure the critical separation of the two tanks as a function of the tank thickness, while keeping the facing area of the tanks and the solution concentration constant. By comparing the critical tank-separation/tank-thickness curves for vessels separated by air, water and constructional materials such as concrete, beechwood and compressed timber (with or without neutron poisons such as cadmium sheet), it is hoped to obtain the basic data needed for the safe and economical design of high capacity solution stores. Each slab tank is treated as a potentially critical assembly in its own right and is filled by remote control from its own solution storage and supply system. Each tank also has its own primary shut-down mechanism — the dumping of 10 litres of fuel solution into a safe cylinder carried on the approach machine table, the separation of the two tables on trip serving as a secondary shut-down device. To economise in fuel, the outward-facing sides of both slabs are reflected by a permanent solid reflector such as polyethylene, while the solid 'decoupling' material under examination is clamped in contact with the inward-facing side of one slab tank. The liquid levels in both tanks are measured by sight glasses and are transmitted by television to the control room, together with the table separation.

Finally, a design study has been carried out for a further solution-cored assembly machine, SORCERER, proposed for use at Dounreay to compare the effectiveness of different materials as neutron reflectors. The significance of a structural material as a reflector is greatest, probably, when it lies in close proximity to a slab-shaped vessel containing solution of maximum reactivity since in such circumstances a normally trivial uncertainty in the reflector

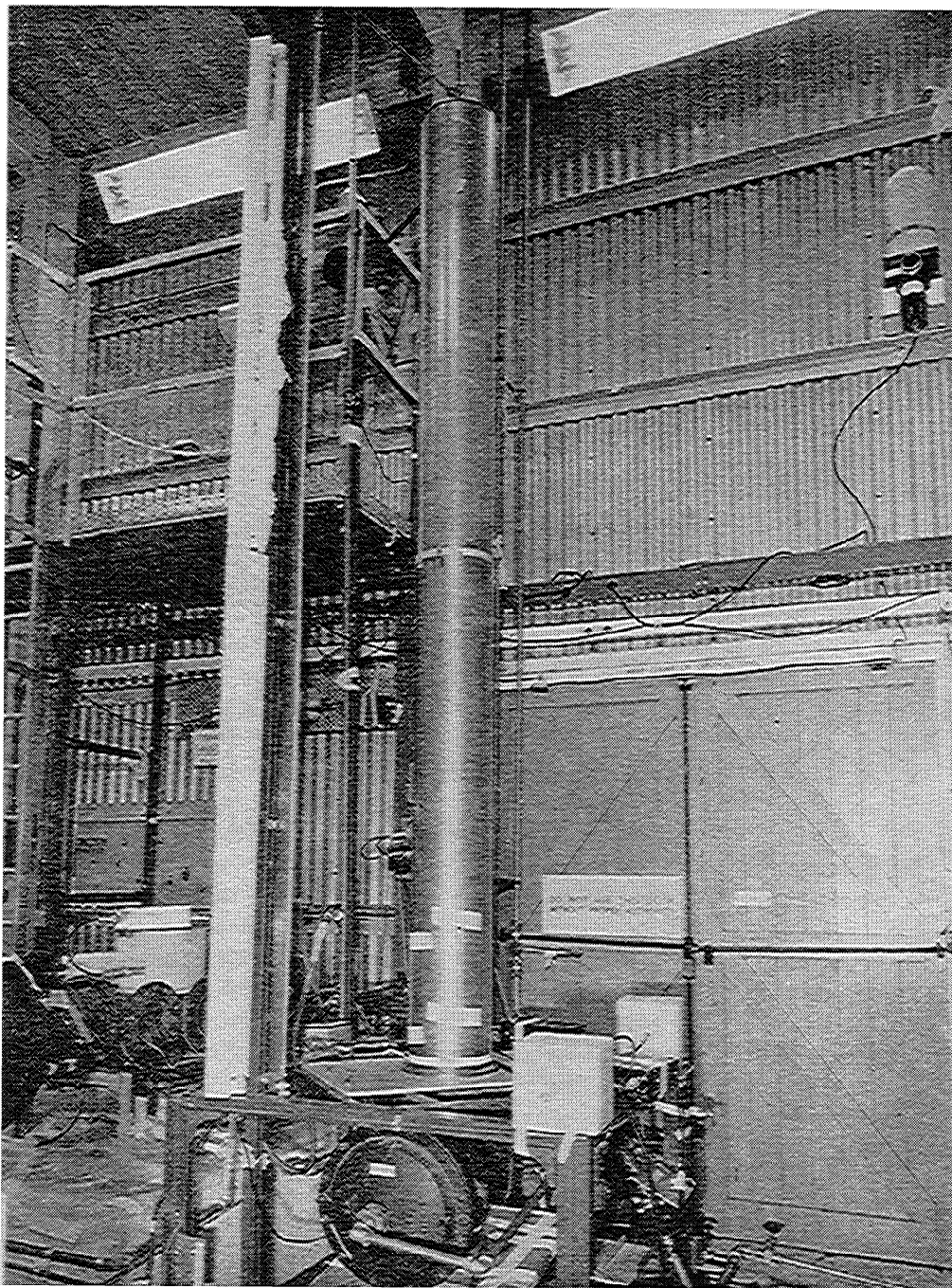


Figure 13. *The PHENIX uranium solution reactor, as used for critical height measurements in a tall unreflected cylinder.*

saving of the material can amount to a proportionately large uncertainty in the safe thickness of the slab-tank. The central feature of SORCERER is, therefore, a horizontal slab of uranium solution contained in a 4 ft square, open-topped tank having a thin aluminium base. The tank is supplied with uranyl fluoride solution from the Cell 1 storage system and the fuel depth

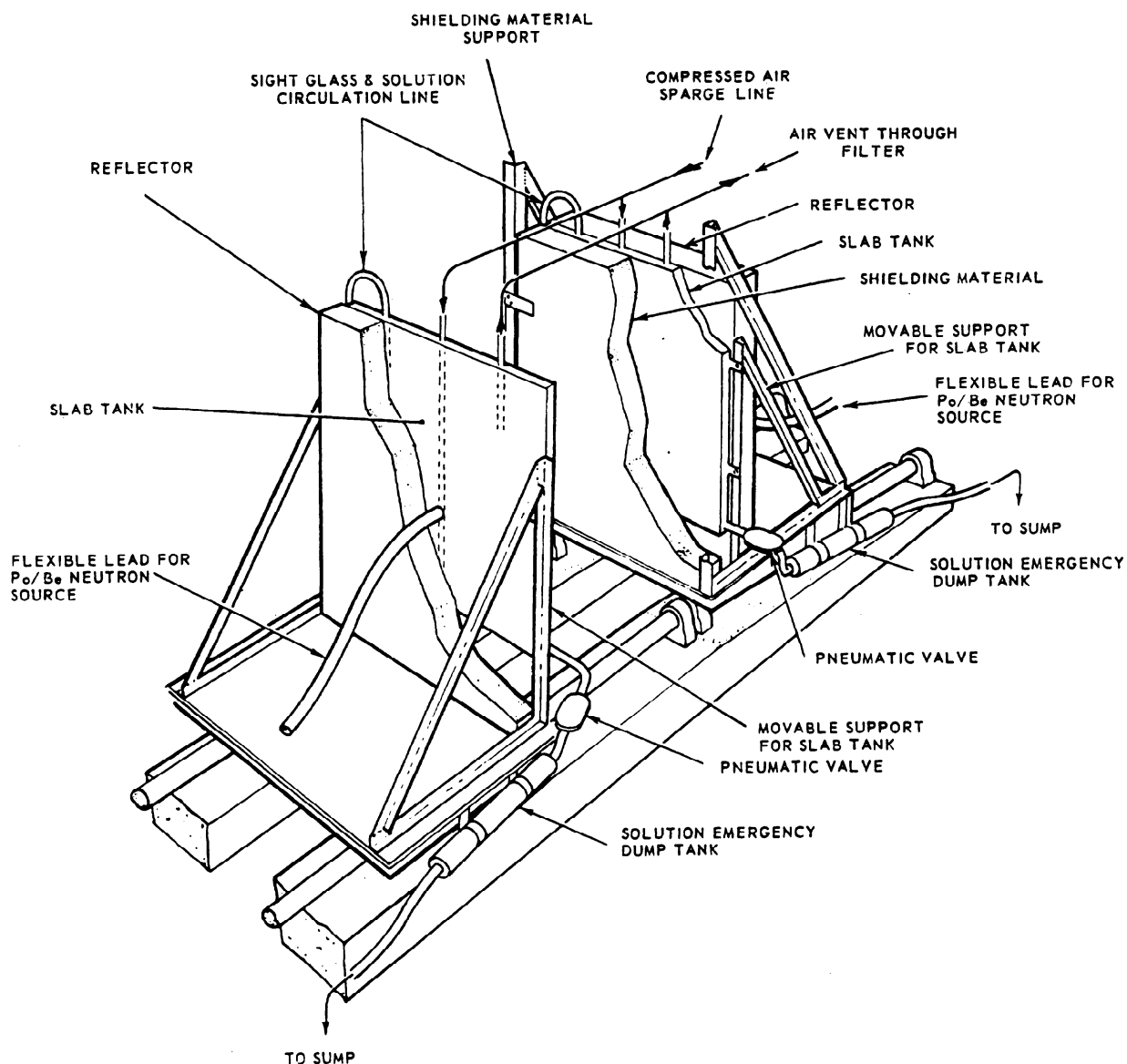


Figure 14. *SIRIUS interacting slab assembly rig (schematic).*

measured by televised observation of a sight glass; a duplicated solution dump system serves as a shut-down device. Arrangements are provided for levelling the tank and also for maintaining its base flat to within 0.050 in. by a removable honeycomb support which contributes a minimum of unwanted neutron reflection. In this, its simplest form, the equipment is suitable for measuring the critical thickness of an isolated and unreflected 4-ft square slab of solution over a range of concentrations and enrichments. The saving afforded by a solid reflector can then be measured directly, as the reduction in this critical thickness, by raising a slab of the test material into contact with the underside of the core tank. A platform, mounted on horizontal rails and raised hydraulically, is used to support the test reflector and permits it to be assembled and accurately aligned at a distance from the core tank. Tests on 'non-infinite' reflectors are carried out using an aluminium honeycomb as a lower support. The effect of water reflectors of various thicknesses

can also be studied, using one of several flooded honeycombs inside a second tank carried on the lower platform. A further addition to the equipment, an upper platform supported inside the solution tank and manually adjustable in height, enables the saving afforded by placing solid reflectors on the two faces of the fuel slab to be measured. This latter facility is intended to confirm the validity of measurements using a one-sided reflector rather than for routine use.

THE OPERATION OF A CRITICALITY LABORATORY

The operator of a critical experiment laboratory is faced with two not always compatible objectives: the absolute requirement to ensure the safety of all personnel, whether they are concerned in the critical mass work or not, together with the only slightly less imperative need to ensure the safety of site installations and of the laboratory equipment and materials; and the need, which derives from the high capital value of the equipment and fuel materials and from the operational difficulties of the work, to obtain the greatest possible yield of critical mass, reactor physics or nuclear data from each programme of experiments. Some indication has been given in the preceding section of the ways these two objectives are met in the United Kingdom laboratories ⁽⁵⁾. It is appropriate, however, to summarize the main features of safety philosophy and experimental procedure adopted in the two laboratories currently in operation.

Safety Philosophy and Procedures

At Aldermaston, all experiments are terminated slightly short of the delayed critical point by an interval dependent chiefly on the familiarity of the system being studied. Each approach to criticality is carried out in a stepwise manner and extreme care is taken to obtain an accurate estimate of the critical point from an early stage in the approach. Whenever possible, therefore, a 'normalizing' experiment using a non-fissile replica in place of the intended fissile core is carried out prior to the 'live' run. The ratio of the response of each neutron detector in the live run to that in the normalizing run, for similar arrangements of the neutron source and detectors and of scattering and absorbing material in the system, then provides a satisfactory measure of the relative neutron multiplication (M) at each stage of the approach. The reciprocal of this relative multiplication ($1/M$), which tends to zero as the system approaches criticality, is plotted as a function of the control variable: table separation, liquid level, etc. Extrapolation of the $1/M$ curve provides an increasingly accurate estimate of the critical point as the experiment proceeds; in addition, it enables the size of the next step to be decided and the increase in multiplication, and hence in counting-rate, corresponding to the chosen step to be predicted. It is the practice at Aldermaston to proceed by stages such that the relative multiplication is approximately doubled in each, the trip level being normally set at 50 % above the predicted counting rate for a proposed step, while the $1/M$ curve is re-examined if the predicted level is exceeded by more than 10 % in any counter.

At Dounreay, account is taken of the fact that reactivity excursions have occurred on quite a number of occasions in critical assembly laboratories and the facilities and experimental procedures have been designed accordingly. The philosophy has been adopted that, if an accident capable of creating a prompt critical condition does happen, there is little that can be done to pre-

vent it by trip-actuated shut-down devices; on the other hand, such devices can do much to limit the total yield of the excursion by suppressing bursts after the first as well as any subsequent fission plateau. It is considered, therefore, that the likelihood of an incident yielding more than about 10^{18} fissions is small. In fact, the shielding of the cells, by distance or concrete or both, has been made such that an incident yielding 10^{19} fissions would not result in a direct radiation dose to personnel exceeding the emergency tolerance level. In a similar manner, the isolation of the uranium cells and the containment afforded by the steel pressure vessel of the plutonium cell provide adequate safeguards against the release of fission products and the natural activity of plutonium from incidents having yields up to 3×10^{18} fissions.

The acceptance of a slight element of risk in the Dounreay experiments leads to a considerably greater speed of working than is possible at Aldermaston, as well as to greater flexibility in the physical arrangement of the assemblies. It is not usually essential to obtain an accurate measure of the relative multiplication early in an approach, and a normalizing run is thus rarely required; a neutron source of adequate emission is essential, but it need not be positioned inside the core, nor need it emit neutrons in a fission spectrum. The steps in an approach can safely be of a size such that the multiplication is increased by a factor of three or four, while the final steps to the critical point can be made equivalent to a maximum reactivity increase of about 0.5 % in k . The actual critical point is located whenever possible by the extrapolation to zero of two slightly supercritical pile period measurements, obtained after removal of the neutron source.

In both United Kingdom criticality laboratories, as elsewhere, the safety of working depends primarily on the experience and vigilance of the personnel rather than on an excess of mechanical interlocks and administrative regulations. It is the procedure, however, before starting a new series of experiments, to prepare a Safety Principles Document or Experimental Plan describing the measurements to be made, the control and safety features of the equipment and the experimental techniques. This document must show that all locally-controlled operations, such as the hand-stacking of a sub-assembly, are demonstrably safe or will be shown to be so by a previous stage in the experiment; it must show that all reactivity additions are reversible; it must consider all foreseeable accidents and indicate the steps taken to avoid them; and it must show that the consequences of the maximum credible accident are acceptable. It is submitted to, and must be approved by, a local Safety Committee, composed of persons largely independent of the operation team, after which the responsibility for the safety of day-to-day operations rests with the leader of the experimental group. The conduct of a critical experiment itself is under the personal control of an authorized Team Leader, chosen for his experience of the type of system being studied; his contribution is particularly valuable in the interpretation of approach curves and in the disposition of the neutron source and counters so as to yield meaningful $1/M$ curves from the earliest possible stage in the approach. During an approach, independent calculations of the multiplication and graphical predictions of the critical point must be made independently by two members of the team, and they must agree on the safety of a further stage before the experiment can proceed. At least two, and preferably three, members of a team must be qualified scientific staff.

The function of shut-down devices in limiting the yield of a prompt

critical excursion has already been described. They serve also to terminate the less severe surge of power likely to remain within the delayed critical region, to be expected following the over-running of a fuel pump or machine drive motor. Whenever possible, two (or more) physically dissimilar shut-down mechanisms are provided on a machine. One of these is arranged to be fairly fast-acting and, in consequence, may control only a small amount of reactivity; the other is usually slower in operation but is capable of shutting the system down entirely in all circumstances. Examples of both are the separation into two halves of a solid assembly and the removal of core or reflector liquid. The insertion of solid neutron absorbers into the core is not favoured, owing to their somewhat unpredictable effects on reactivity in frequently-changed core configurations and to the difficulty in providing spaces within the core to contain the absorbers while preserving a 'clean' geometry. Fast-acting 'safeties' frequently invoke the direct fall under gravity of part of a solid or liquid core or — less usually — a reflector. Slow-acting devices may require an electrical supply to a motor, either to drive the two halves of a solid assembly far apart horizontally or to remove the entire contents of a liquid core by pumping; such mechanisms cannot be made entirely fail-safe, though the chances of failure can be made almost negligible by the provision of alternative mains and battery supplies, the latter preferably unfused. In systems, such as bare solution cores, where two different safety devices are difficult to provide, a single one (dumping of solution), duplicated in its entirety, is used. This insures against failure of the mechanical or electrical parts but not against the physical inadequacy of the method of reducing reactivity.

The rates of reactivity addition are limited during particular experiments by the motor or pump speeds and by limit or level switches restricting the ranges of availability of the several speeds. However, the gear ratios of mechanical drives, the displacement of pumps, and the positions of limit switches are all adjustable and their settings are considered as part of each Experimental Plan. Interlocks and sequencing circuits are used to ensure that safety devices are cocked and that a neutron source is inserted prior to starting a critical approach. Beyond this, the conduct of an experiment is very largely at the discretion of a team leader; in particular, many — though not all — of the radiation sensing instruments can be bypassed, and it is the experimenter's responsibility to ensure that an adequate number of effective detectors are available to initiate a trip at any stage in an approach.

Economic Operation of Facilities

The high cost of critical assembly experiments derives from two main causes: the relatively high investment of fissile materials, and the need to conduct the experiments without hazard to persons and equipment. The former is determined by the critical masses and volumes of the systems being studied and cannot be reduced materially as long as a direct measurement of the critical parameters is required. The latter — which is reflected in the costs of shielded cells, containment vessels, complex instrumentation, remotely-controlled operations and active-handling procedures — is part of the safety philosophy of the nuclear industry and cannot be compromised. It is therefore essential to obtain the highest possible utilization of the facilities, materials and staff if criticality studies are to be economically worthwhile. This need can be met partly by designing the buildings, assembly machines and other

installations to be of high flexibility and partly by extracting from each programme of experiments all the information readily obtainable regardless of its relevance to the immediate critical mass determinations. To conclude this paper, some observations will be made on how these objectives are being approached in the two laboratories in question.

It is a pre-requisite of flexibility that several assembly machines are available. For work on solid systems, it is not unduly inconvenient for these to be within the same cell, though each should be provided with its own control instrumentation. For work on solutions or on a mixture of solid and solution systems, it is almost essential that each apparatus shall be in a separate cell if work is not to be hindered by the impossibility of setting up one rig when an adjacent one is operating in a near-critical condition. Even where separate machines and cells are available it is often found that the major part of the time is occupied by engineering or other preparatory work and it is probable that a critical facility concerned with a variety of systems cannot be operated with reasonable efficiency if fewer than three cells are available; only one or two of these are then likely to be in use for actual measurements at any one time.

Several procedures have been adopted at Dounreay in an attempt to reduce the proportion of time spent on setting up an experiment. These include the use of a standard control wiring installation, incorporating a modular system of plug-in relays to provide interlock and sequencing facilities and including a telephone-type distribution or 'jumper' panel at which all the cross-connections needed to change from an old rig to a new and entirely different one can be made and tested in a few hours. It is the practice to pre-test all new control circuits prior to installation, or even to delivery, of a new rig by using an electrical rig simulator. Likewise, the hydraulic behaviour of the liquid circuits of solution rigs is tested in a mock-up prior to being set up in a cell. Closed-circuit television is frequently used for transmitting to the control room physical measurements such as liquid levels, platform positions and even some meter dial readings in preference to more conventional electrical methods. This is a particularly convenient procedure where the need is of short duration and where faulty instrument indications must make themselves immediately apparent.

A final requirement of a versatile criticality facility concerns the ancillary services. An adequate instrument department, integral with the laboratory and familiar with pneumatic and hydraulic as well as with the more conventional electronic and electro-mechanical techniques, is highly desirable. For work on solutions, and probably also on solid moderated fuels or 'mock-precipitates', there must be a chemical technology department within the facility. Mechanical engineering services must be available for programmed work such as core tank changes and to provide day-by-day services in support of the less predictable needs of the experiments; the major design of new machines is normally outside the scope of the laboratory staff, though it remains their responsibility to specify their requirements. Ready access to computer facilities, if necessary over a telex data link, is desirable for numerous purposes, from the routine checking of pulse counting channels for statistical purity to the analysis of foil activation data, the computation of reactor parameters from distribution measurements and the treatment of reactor period data.

The principle of exploiting each experiment to the full can be followed

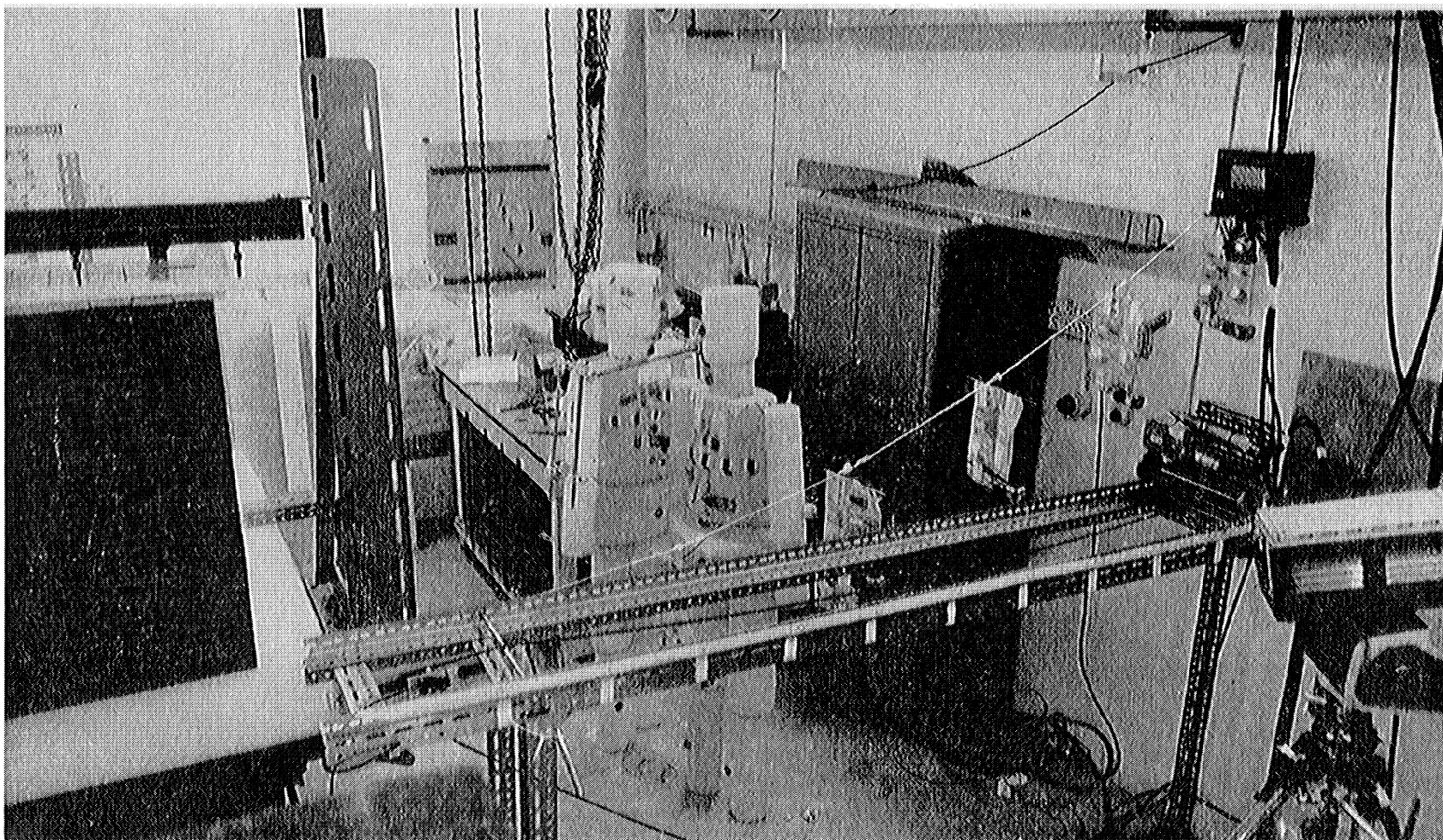


Figure 15. *The use of the TESSIE reactor for the irradiation of dosimetry locket mounted on "phantoms" and at other fixed locations in the vicinity of the critical assembly.*

in a general way by carrying out neutron-distribution, integral reactor spectrum studies, importance or replacement experiments and fission rate measurements whenever opportunity permits, and in as comprehensive a manner as possible; some of these studies are only practicable in a critical system and may require operations up to a power of a few watts. In particular instances, other extensions of the scope of critical mass experiments are possible. One such extension, shown in Figure 15, has involved the use of the Dounreay TESSIE assembly machine for the irradiation of neutron dosimeters and 'phantoms', as part of a programme to develop a critical incident 'loquet' for use in fissile material processing plants throughout the United Kingdom. In this, operation of the assembly at a power of over 1 kW was required, until the yield of the run exceeded 10^{17} fissions and the radiation dose to the nearest phantom was over 300 rad. In another experiment, special core tanks in the PANTHER equipment are being used, in conjunction with a neutron chopper, for time-of-flight measurements of the spectrum in plutonium solutions of various concentration; the differential spectra thus obtained are being compared with the integral measurements made in the critical spheres. The same vessels are also being used to obtain the $\eta(239)/\eta(235)$ ratio.

In conclusion, it may be stressed that continuity of work, and hence the economic usage of a facility, can only be ensured by including in its programme one or two longer-term experiments able to absorb the surplus efforts of scientists, but which do not make very heavy demands on the chemical or engineering resources of a laboratory.

Examples of such work are the fundamental neutron interaction experiments carried out on multi-component metal systems at Aldermaston ⁽⁴⁾ and the basic solution critical parameter surveys in progress at Dounreay ⁽⁴⁾ in the PHOENIX and TOAD reactors ⁽⁶⁾. The former have led to the steady development of a widely applicable theory, using the concept of an interaction parameter, for calculating the safe number of fissile units in an array or the safe spacing of such units. The latter have embraced a wide range of core shapes, sizes and concentrations and are gradually defining the bounds of uranium solution criticality in the medium enrichment range. Both types of experiment have served as a reservoir of effort, available for urgent plant safety work as occasion demands, and have acted as a training ground for new staff.

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